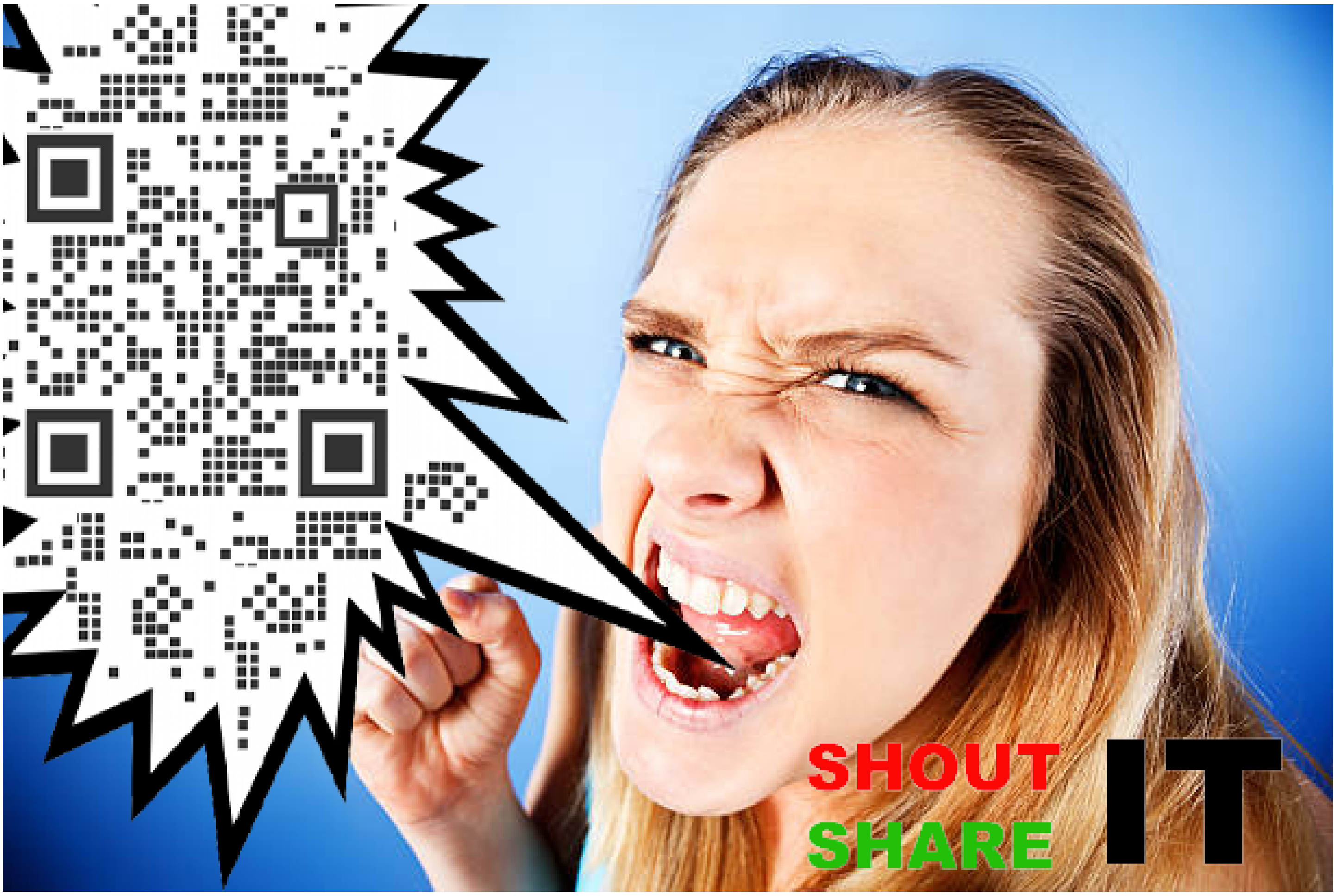
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AUSTRALASIAN ANTARCTIC EXPEDITION

1911 - 1914.

UNDER THE LEADERSHIP OF SIR DOUGLAS MAWSON, D.Sc., B.E.

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Series A.—Geography, Physiography, Glaciology, Oceanography, and Geology.

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THE

METAMORPHIC ROCKS OF ADELIE LAND

SECTION I.

BY

F. L. STILLWELL, D.Sc.,

University of Melbourne

(Geologist to the Australasian Antarctic Expedition).

With Thirty-five Plates and Fourteen Figures in the Text.

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CORRIGENDA.

Page 13.—In second last line of second paragraph *for* " Evidenec " *read* " Evidence."

Page 29.—Table I.—In column 1, *for* iron ore .... 3·0 *read* iron ore .... 2·7
In column 10, *for* mica .... 10·8 *read* mica .... 10·5
In column 12, *for* hornblende .... 56·3 *read* hornblende .... 60·0
epidote .... ·7 epidote .... 1·0
iron ore .... ·7 iron ore .... ·6

Page 39.—In footnote, *for* J. C. H. Mengaye *read* J. C. H. Mingaye.

Page 48.—The first portion of the second line should read " in varying degrees on those of an adjacent zone."

Page 55.—In the first reference at the foot of the page, *for* Journ. Geol., vol. 3, p. 1, *read* Journ. Geol., vol. 23, p. 1.

Page 63.—In the list of projection values, *for* f. .0·20 *read* f. .20·0.

Page 87.—In the group values of Rainy Lake gneiss, *for* S. .74·9 *read* S. .74·0.

Page 94.—In seventh line from bottom, *for* (p. 39) *read* (p. 89).

Page 95.—In fourth line of middle paragraph, *for* (p. 107) *read* (p. 105).

Page 96.—In sixteenth line from bottom, *for* (p. 45) *read* (p. 47).

Page 117.—In ninth line from top, *for* (p. 41) *read* (p. 141).

Page 195.—In sixteenth line from bottom, *for* (p. 121) *read* (p. 221).

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UNIV. OF CALIFORNIA

THE METAMORPHIC ROCKS OF ADELIE LAND.

SECTION I.

By F. L. STILLWELL, D.Sc. (*Geologist to the Australasian Antarctic Expedition*),
University of Melbourne.

INTRODUCTION.

Adelie Land is a portion of the Antarctic Continent which lies in the region surrounding Long. 143° and Lat. 67°. It consists for the most part of a huge ice-covered plateau which rises rather steeply from the coast and reaches a height of over 6,000ft. at 300 miles inland. It appears, at first sight from the ship, as the side of a vast dome-shaped shield of ice, which descends to the ice cliffs or ice barrier on the seaward side and rises to about 1,500ft. on the southern horizon.

The ice cliffs present a vertical face varying between 80ft. and 120ft. in height, and delimits the boundary of the land ice sheet. In many cases the cliffs form the edge of floating glacier tongues or marginal shelf ice, but as the *Aurora* traced the coast line from Cape de la Motte to Commonwealth Bay, rock could be frequently seen at the base of the cliffs. Yet these exposures remained quite inaccessible to us, and only those outcrops which rise 100ft. or more above sea level and which break the monotonous line of ice cliffs could be reached by sea or land. These latter outcrops are rare, and while they can be readily seen from the ship they are only found and approached with difficulty from the landward side. Rarer still are the nunataks, or islands of rock in the snow fields, and our knowledge of the rocks of the hinterland remains very largely dependent on the study of the glacial debris on the moraines.

Three small rocky promontories exist along the 60-mile stretch of coast line of Commonwealth Bay—a broad open bay about 40 miles across the headlands. Of these the middle one is Cape Denison, on which the Main Base of the Australasian Antarctic Expedition was situated. The western rocks, always visible from Cape Denison, form Cape Hunter. The bay is studded in the centre by the Mackellar Islands, a group of low-lying islands due north of Cape Denison. East of the bay is the Cape Gray Promontory, thickly fringed with the numerous small rocky islets which constitute the Way Archipelago. These islets mostly lie in a 2-mile zone around the edge of the ice cap, and one of the largest is Stillwell Island, on which a landing was made. On the eastern side of the Cape Gray Promontory, facing Watt Bay, are the rock outcrops which have been called Garnet Point and Cape Pigeon Rocks.

Madigan Nunatak and Aurora Peak, the two remaining rock exposures dealt with in this thesis, are widely separated nunataks. Madigan Nunatak is 2,400ft. above sea level and lies on the ridge which gradually slopes down to Cape Gray, 18½ miles to the north. Aurora Peak is the more easterly and lies on the west side of the Mertz Glacier, 1,750ft. above sea level and about 60 miles distant from Cape Denison.

The rock specimens and the field data of these nine rocky areas were obtained by the following :—

Cape Denison	Large rock collection made during the winters of 1912 and 1913 by Sir Douglas Mawson and Stillwell.
Cape Hunter	Visited in December, 1913, by Sir Douglas Mawson.
Gt. Mackellar Island	Visited in December, 1913, by Sir Douglas Mawson.
Stillwell Island	Visited in December, 1913, by Sir Douglas Mawson.
Cape Gray	Visited in summer, 1912-13, by Stillwell's sledging party.
Garnet Point	Visited in summer, 1912-13, by Stillwell's sledging party.
Cape Pigeon Rocks..	Visited in summer, 1912-13, by Stillwell's sledging party.
Madigan Nunatak ..	Visited in summer, 1912-13, by Stillwell's sledging party.
Aurora Peak	Visited in summer, 1912-13, by Madigan's sledging party.

The total rock collection of the Australasian Antarctic Expedition is very large, but the bulk of it comes from the glacial moraines at Cape Denison, and is not treated in the following. The specimens secured by the sledging parties had necessarily to be limited in size and number. Madigan collected the specimens at Aurora Peak, and Laseron was a valuable assistant in looking after the rocks obtained by my sledging party. No geological specimens were obtained by the other three sledging parties, except a stony meteorite, a very extraordinary find made by Bickerton's sledging party on the ice plateau.

We have only been able, up to the present, to deal fully with the rocks which were found *in situ*. This part is an essential preliminary to the study of rock types from the moraines. Even this portion could not have been concluded without the active co-operation of friends and supporters of the A.A.E. We are greatly indebted to Mr. Herman, Director of the Victorian Geological Survey, who sanctioned the assistance of the Victorian Geological Survey Laboratory. The 15 rock analyses that are now presented are the work of the analysts in this laboratory, working under the supervision of P. G. W. Bayly.

Though a good portion of the work has been done while associated with the Adelaide University, it was commenced and finished at the Melbourne University. Its progress throughout has depended wholly on the assistance afforded by the Geological Department of the Melbourne University and by Professor Skeats. The " sinews of war " have here been provided in a very large number of excellent rock sections and much useful criticism has been levelled during discussion at some of the conclusions.

The illustrations at Cape Denison were obtained by Hurley, the official photographer. Laseron acted as photographer on my sledging trip, and obtained some very fine results. The photographs of the rock specimens and the microphotographs of the sections have been prepared by myself with the apparatus and facilities in Melbourne.

Finally, we must record the active sympathy of the leader of the Expedition, Sir Douglas Mawson, who entrusted me with the work.

CHAPTER I.

SUMMARISED ACCOUNT OF THE METAMORPHIC ROCKS FOUND *IN SITU* IN ADELIE LAND.

In all the outcrops in Adelie Land accessible to us, varying types of crystalline schists have been found. The chief types may be enumerated as follows :—

Locality.	Crystalline Schist.	Pre-existing Rock Type.
Cape Hunter	Phyllite	Clay sediment
Cape Denison	Granodiorite gneiss	Granodiorite
	Aplite gneisses	Aplites
	Amphibolite series	Dolerites
Gt. Mackellar Is.	Granite gneiss	Granite
	Amphibolite	Dolerite
Madigan Nunatak	Plagioclase pyroxene gneiss	Dolerite
	Hypersthene alkali felspar gneiss	Granite
Aurora Peak	Hornblende plagioclase pyroxene gneiss	Dolerite
	Garnet hypersthene alkali felspar gneiss	Granodiorite
Cape Gray	Plagioclase pyroxene gneiss	Dolerite
	Garnet cordierite gneiss	Clay sediment
Garnet Point	Amphibolite	Dolerite
	Cyanite biotite gneiss	Clay sediment
	Garnet felspar gneiss	Sediment (probably)
Stillwell Island	Plagioclase pyroxene gneisses	Dolerite
	Amphibolites	Dolerite
	Acid hypersthene gneisses	Granitic veins and diorite
	Garnet felspar gneiss	Sediment (probably)
Cape Pigeon Rocks	Amphibolites, etc.	Dolerite
	Garnet gneisses	Sediment (probably)
	Garnet hypersthene biotite gneiss	Diorite (?)

In all cases except Cape Hunter there are two main rock types—an acid type and a basic type. The basic type represents the metamorphic equivalent of a basic igneous rock that has intruded the granitic rock or the sedimentary rock before the metamorphism. In all cases the primary dyke origin of the basic type has been established with certainty.

At the most westerly area, Cape Hunter, there is an old sedimentary series, now represented by a phyllite. Nine miles east of Cape Hunter lies the granodiorite gneiss of

Cape Denison and its associated basic dykes. Twenty miles further east again, the metamorphosed sediments appear again at Cape Gray in the form of garnet cordierite gneisses and garnet felspar gneisses. Inland from Cape Gray granitic areas have existed at Madigan Nunatak and Aurora Peak. These facts are illustrated in the accompanying section (fig. 1).

In the section the granitic mass at Aurora Peak is assumed to be intrusive into the original sediments, because altered granitic dykes appear on Stillwell Island and Cape Pigeon Rocks cutting the garnetiferous gneisses. The altered granitic dykes are not necessarily to be associated with the primary granitic masses of Aurora Peak and Madigan Nunatak. The presence of tourmaline in the Cape Hunter phyllites is the only evidence available for representing the intrusive nature of the Cape Denison granodiorite gneiss.

The outcrops dealt with are isolated areas extending over 60 miles of country. Over this great distance it is only to be expected that varying conditions of metamorphism would be found. On the west, at Cape Hunter, we have dominant epi-zone metamorphism. At Cape Denison the metamorphic conditions are intermediate between those of the epi zone and meso zone of metamorphism, with variation in both directions. The amphibolites which are completely recrystallised rocks sometimes approach the character of meso zone rocks and sometimes are more like epi zone rocks. On the Cape Gray Promontory, where the garnetiferous gneisses abound, and at Madigan Nunatak and Aurora Peak evidence of kata zone metamorphism is found in all cases. At Madigan Nunatak very remarkable epi zone metamorphism is superimposed upon the kata zone metamorphism, while between Madigan Nunatak and Cape Gray and at Aurora Peak meso zone metamorphism is superimposed upon the kata zone metamorphism. There is, therefore, quite a distinct regional distribution of the metamorphic products of Grubenmann's three metamorphic zones and an argument in support of the general conception produced.

The detailed studies of the dyke series at Cape Denison and at Cape Gray have produced some extraordinary results. In these, considerable use has been made of the Rosiwal method of volumetric rock analysis for the purpose of obtaining relative mineral composition of different specimens. The absolute mineral composition could only be obtained by three determinations in three planes at right-angles—a process too tedious to be of any service. Yet the mineral composition of schists can be compared with advantage in rock sections which have been cut from a constant direction relative to the plane of schistosity.

The Cape Denison dyke series ranges from epidote biotite schists at Azimuth Hill, on the western part of Cape Denison, through biotite amphibolites to amphibolites on the eastern side. Lawsonite has been detected in several cases, and lawsonite amphibolites have been described. In the mineral composition of the series it is found that the percentages of epidote and biotite vary sympathetically and inversely with

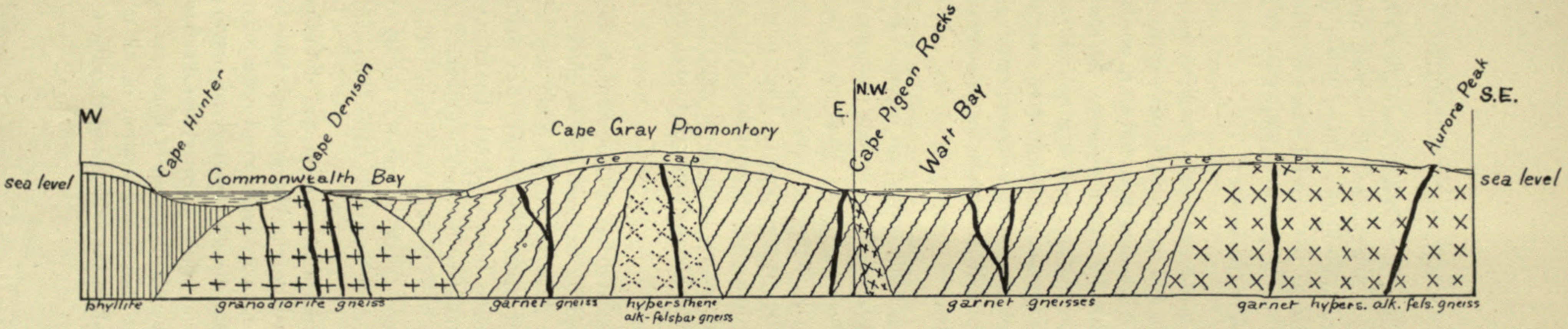
W
Cape Hunter
Cape Denison
Commonwealth Bay
Cape Gray Promontory
E.
N.W.
Cape Pigeon Rocks
Watt Bay
Aurora Peak
S.E.
sea level
ice cap
ice cap
sea level
phyllite
granodiorite gneiss
garnet gneiss
hypersthene alk-felspar gneiss
garnet gneisses
garnet hypers. alk. fels. gneiss

Fig. 1.

Sketch Section from Cape Hunter through Cape Denison and Cape Pigeon Rocks to Aurora Peak.

Horiz. Scale, 8 miles to 1 inch.

the percentage of hornblende. There are, however, exceptions both at Cape Denison and Mackellar Island, but these can be explained by varying metamorphic conditions. The chemical composition of the epidote biotite schists differs distinctly from that of the amphibolite, though both possess the general characteristics of a basic igneous rock. The chemical composition of the biotite amphibolites is calculated to be near the mean of the two end members of the series.

Extraordinary examples of metamorphosed xenoliths have been found in an amphibolite dyke at Cape Denison, and include both the cognate and accidental types. These bodies were caught up by the invading dyke and set in position before the development of the amphibolite characters by metamorphism. In some instances they still preserve a very remarkable angular outline, but they are now an integral part of the metamorphic rock, and the foliation passes through them irrespective of their outline. The cognate xenoliths now possess the same recrystallisation products as the dyke. The accidental xenoliths are undoubtedly foreign to the primary dyke, and bear relation to the enclosing granodiorite gneiss.

Quite distinct from these xenolithic bodies are certain varying rock types which are enclosed in the amphibolite dykes. These include epidosites, chlorite rock, biotite hornblende schists, and biotite felspar schists. These rocks bear definite relation to the development of the metamorphic characters, and can only be adequately explained by an hypothesis depending on the metamorphism. Their mineral composition shows that their chemical composition is quite distinct from that of the amphibolite from which they were derived. The proved difference in chemical composition involves the migration and segregation of material under metamorphic conditions, and is called metamorphic differentiation.

In addition to the sharply-walled dykes at Cape Denison there are isolated patches of amphibolite completely enclosed by the granodiorite gneiss. Argument is deduced to show that these amphibolites, differing only in grain size, have once been part of the dyke series. This means that these " inclusions " are younger than the enclosing gneiss, and the dyke channels have been rendered discontinuous during the metamorphism. In some cases the boundary between amphibolite and granodiorite gneiss has been destroyed and replaced by a gradual transition. The destruction of a pre-existing boundary by the migration of material across it during metamorphism is called metamorphic diffusion. In all cases of transition there is no evidence of refusion.

The processes of metamorphic differentiation and diffusion are very limited in range and produce the exceptional types. Nevertheless, they have been found to be applicable to localized portions of many widespread areas of crystalline schists. In several cases they produce results directly opposed to previous conclusions. The assumed evidence, for example, on which is based the conclusion that amphibolites can be produced by the extreme metamorphism of limestones in Canada, is rendered invalid. The evidence demands the reconsideration of all conclusions in areas of crystalline schists which are based on the evidence of transition.

In the Cape Gray dyke series the metamorphism of the primary dolerite has occurred under very different conditions from those which operated at Cape Denison. The mineral changes have occurred under conditions which have not destroyed the dyke form. The dykes branch and send forth little tongues into the garnet gneisses, in the same manner as in unmetamorphosed regions. Minerals and structures of the primary dolerite may be recognised, but in all cases the metamorphic features dominate the igneous character. The mineral changes can be directly traced and prove to be very interesting. The relic pyroxene of the dolerite is usually found to be crowded with minute, dusty inclusions of ilmenite (schiller inclusions). On recrystallisation the pyroxene may pass into a granular aggregate of clear secondary pyroxene, including both hypersthene and augite, while the minute ilmenite inclusions coalesce into crystal units. If the pyroxene then passes over to hornblende, amphibolites are produced. The pyroxene may also react with the anorthite molecule of the labradorite and produce garnet and quartz. The formation of the latter may be preceded by the development of a diablastic intergrowth of felspar with vermicular pyroxene which may extend as a reaction rim around the pyroxene crystals. If part of the pyroxene is amphibolised at the same time, a garnet amphibolite is produced.

The grain size of the recrystallised rock depends entirely upon the metamorphic conditions. An early stage of the recrystallisation of a dolerite may be the production of a fine-grained aggregate consisting of felspar and augite. A later stage involves the growth of large crystals at the expense of smaller ones, and the production of a moderately coarse grained rock. Rosiwal analyses have demonstrated the similarity in percentage in mineral composition between a fine-grained type at Cape Gray, a coarser type at Aurora Peak, and still coarser type at Madigan Nunatak. As the dyke origin of the Cape Gray type is certain, sound evidence is thus brought forward concerning the origin of the plagioclase pyroxene gneisses at Aurora Peak and Madigan Nunatak. In this case, and in many others in this series, there are similarities between these Antarctic rocks and the rocks called pyroxene granulites in Saxony, and norite in India. Evidenec is therefore provided for the metamorphic nature of these rocks.

The acid hypersthenic gneisses of Madigan Nunatak, Aurora Peak, Stillwell Island, and Cape Pigeon Rocks possess affinities due to similar conditions of complete recrystallisation. The primary igneous nature of the first two is determined by their chemical composition, which closely resembles that of granites, while the igneous nature of one example from the third occurrence is indicated by its dyke form. These rocks are found to be very closely related to the hypersthene rocks in India, which have been described as charnockite, and which have been looked upon as igneous rocks that have consolidated under phenomenal conditions. The metamorphic nature of the Antarctic rocks is maintained, and argument is found to show that the charnockites are also metamorphic rocks which have been completely recrystallised under deep-seated metamorphic conditions.

Apart from the metamorphosed dyke series the Cape Gray Promontory is noted for its highly garnetiferous gneisses. The garnets are most remarkable at Garnet Point and at Stillwell Island, where they are found 1½in. to 2in. in diameter, and give the outcrops a curious mottled appearance. These large garnets are always partly altered to biotite and quartz, which appear in cracks and around the edges of the crystals. Cordierite, sillimanite, and corundum are found in different specimens and indicate the high alumina content. Very beautiful pleochroic haloes are found in some of the biotites of these gneisses. Some show an inner nucleus and an outer corona, while some change the colour of the biotite in their sphere of action from a pale green to a brown.

At Garnet Point and the Cape Pigeon Rocks dykes containing prominent garnet and felspar cut the garnet gneisses. A single specimen from one of these has indicated its relation to the hypersthenic felspar gneisses on Stillwell Island. Very extraordinary variation has been discovered in the mineral content of these hypersthene garnet rocks, which correspond to the intermediate members of the charnockite series. At one end of a specimen 3in. long, garnet is present, and has been produced by the reaction between biotite and plagioclase and quartz, while, in a section cut from the opposite end of the specimen, garnet and all evidence of reaction are absent. In other cases biotite and quartz result from reaction between hypersthene and orthoclase, while in one case the garnet seems to be formed directly from the hypersthene. Garnet-forming conditions may therefore be highly localised, and all the evidence that has been collected is antagonistic to Fermor's conception of an infra-plutonic zone—a deep zone in the earth's crust which is supposed to be characterised by garnets. The evidence reminds us that the metamorphic zones are not defined by certain depths in the earth's crust, but by a set of physico-chemical conditions.

The study of the examples in Adelie Land of destroyed igneous boundaries, of the metamorphic differentiation products, of the mineral changes, and of the development of large crystals during recrystallisation leads us to believe that solid diffusion in rocks is an important factor that needs to be considered in the detailed study of the development of the crystalline schists.

CHAPTER II.

THE PHYSIOGRAPHY OF CAPE DENISON.

The rocky promontory of Cape Denison covers approximately half a square mile. It forms a roughly triangular area with a base of three-quarters of a mile on which the rocks rise to a height of 140ft. above sea level, when they disappear beneath the glacier ice. On the east and the west the uniform ice cliffs of Commonwealth Bay give way to rocky cliffs, which are first of similar height but which descend to sea level as they continue north (Plate XIV., fig. 1). The shore line is indented, and one small bay is 400yds. deep and 100yds. broad at the mouth, and, as it broadens towards the head, it forms an excellent boat harbour. This boat harbour is actually an extension of the valley depression in which the hut is situated—a miniature drowned valley.

The rocks remain uncovered throughout the whole year. A little more than the average area is exposed by the summer thaw, and the winter snow drifts do not bury much on account of the incessant wind.

Agents of Denudation.

The promontory may be described as a miniature mountain area. It is rugged, and possesses steep rock faces and sharp ledges (Plate XVI., fig. 2). It is carved by four parallel valleys, and the intervening ridges are crowned by numerous small peaks (Plate XV., fig. 1). The sculpturing is the combined effect of different factors which we tabulate and discuss in order, as follows :—

1. Glacier Action.
2. Frost Action.
3. Water Action.
4. Wind Action and Atmospheric Weathering.
5. Shore Ice Action.
6. Nature and Structure of the Rock Mass.

1. *Glacier Action.*—The area reveals abundant evidence of glaciation. Glacial erratics are promiscuously scattered everywhere. Apart from the well-defined moraines the distribution is as abundant on the higher ridges as in the lower valleys, and the erratics are frequently seen perched in curious positions on the highest crags. Some of the erratics have polished faces and rounded edges, and some show glacial striæ, while others are quite subangular. Some weigh several tons, and many consist of foreign rock types. Polished, striated, and grooved surfaces of the "*in situ*" rock are to be seen. Very highly polished surfaces (Plate XVIII., fig. 1, Plate XXII., fig. 2) are quite characteristic of the peripheral area below the 40ft. contour level. Above this belt

the broad outlines of rounded bosses of rock are always indicative of glacial planing, but in minute detail the surface is usually found to be minutely pitted and roughened by the unequal erosion of the constituent minerals. Nevertheless polished and striated surfaces can be discovered, and one block about 9ft. square with long, well-marked, parallel striæ was photographed (Plate XVIII., fig. 2). The striæ trend N. 32° E.

The existence of a lower zone of relatively polished rock and a higher zone of relatively unpolished rock is a noteworthy feature. It is believed that the roughnesses on the surface of the rocks is due to abrasion of millions of snow grains. In this case the upper zone must have been exposed for a longer time than the lower (below the 40ft. contour), which has been relatively protected. But the shore line is capped for almost the whole year by an ice foot, which is stationary and protective, and wave erosion has only opportunity for limited action. The ice foot is usually about 15ft. high, and may provide a simple explanation of the preservation of the well-polished surfaces on the border zone of land and water. Then if we assume a slight relative and recent uplift we may easily explain a relatively protected zone up to 40ft.

The highest point of the Mackellar Islands is about 40ft. above sea level, and the notes made by Sir Douglas Mawson show that the character of their surface is the same as the peripheral area of Cape Denison. Though no highly polished surfaces or striæ were found, the general surface of the islands is flat and in part very smooth, with the prominences well rounded. Roughnesses can be explained by very recent disintegration.

Glacial plucking is evident. When the glacier has passed over a sloping resistant rock face the lee side is often found to be steep, because the rock has been plucked out by the onward travel of the ice.

Lakes.—Five small glacial lakes are present in this area, and their position is shown in the locality plan, and their manner of occurrence is illustrated in Plate XXXI., fig. 2. Four of these are almost round in shape and 30yds. to 40yds. broad. Lake II. is not quite so broad, and its length is more than three times its breadth (Plate XVII., fig. 1). We mention this point because the direction of the glacial movement has not corresponded with the long axis of the lake. Lakes III. and V. (Plate XX., fig. 1) are situated on valley floors, while Lake IV. (Plate XX., fig. 2) is on the highest level—about 120ft. above sea level. Lake IV. is bounded on the northern side by a rock wall thickly banked with morainic material (Plate XXI., fig. 2). The lakes average about 20ft. in depth, and they represent depressions gouged out of the rock floor by the forward movement of the ice.

Valleys.—There are four parallel, broad-bottomed, shallow valleys. In parts their sides are moderately steep, and their trend is N. 15° W., which is very nearly coincident with the strike of the rocks (N. 4½° W.) (Plate XV., fig. 2, Plate XVII., fig. 2). This direction makes an angle of 45° with the direction of the trend of the glacial striæ, and the origin of these valleys is an interesting problem which will be introduced after other sculpturing factors have been discussed.

2. *Frost Action.*—Frost has played a subordinate part in the sculpturing of this area. In the summer we may get daily thawing and freezing. The thaw water finds its way down rock joints, and, refreezing, tends to force open the joints and perhaps cause fresh fracture. Boulders with planes of ready percolation, *e.g.*, bedding planes, may be seen completely shattered into flakes parallel to the bedding plane. Areas were photographed (Plate XX., fig. 4) which consist of angular boulders twisted and jumbled into a very confused state as the result of displacement by frost. These areas are most marked where the drainage of thaw water is slow and impeded. In this way frost action has helped to demolish the little mountain peaks and ridges.

3. *Water Action.*—The prevailing winds blow from the south, and, being very cold and constant, do not permit much thaw. Given, however, calm weather, a clear sky, and a bright sun, the thaw is rapid. Such days are not frequent. On one occasion in December, 1912, the thaw water, draining off the moraines, was dammed back for a while by ice. When the barrier gave way about mid-day a small cataract rushed down the side of the valley in which the hut was situated, and in about three hours the stream carved a channel through 6ft. of glacier ice down to bed rock. Stones and pebbles were rolled along the course with great energy.

Running water is uncommon, and is usually too insignificant in quantity to have much bearing on the rock sculpturing.

Marine erosion also must be slight on the mainland, for the weather is constantly "off-shore," and an ocean swell is rarely seen, even though there is open sea throughout the whole year. Except for about one month during the year the shore is protected by an ice foot.

4. *Wind Action.*—The violence of the wind in Adelie Land is impressive by reason of its possibilities. The constant blast of snow grains against the rock makes all surfaces minutely rough and pitted. The effect of the abrasion on timber became very marked on the roof of the hut and on all pieces of exposed box timber. The softer constituent minerals in the gneiss, such as mica, are worn away much more rapidly than the harder quartz and felspar. The etching is very prominent in specimens of the limestone schists found on the moraines, and the harder portions are raised in strong relief. Nevertheless, it is quite certain that the rocks are relatively unweathered and fairly recently uncovered in comparison with the Madigan Nunatak. The wind affects the topography by preventing soil deposition; the surfaces of the rocks and moraines are swept clean of all fine rock detritus that is not held down by the weight of boulders or embedded in ice, and this detritus finds permanent lodging only in the cracks and joint planes of the rocks. It is interesting to recall that occasionally in the winter pebbles were heard to strike the roof of the hut just as if some one outside were throwing stones. Grit may always be discovered when one displaces some of the larger boulders on the moraines.

5. *Shore Ice.*—Sea ice did not remain in Commonwealth Bay for more than a couple of days during 1912 and 1913; in the boat harbour, however, the ice was able to remain and thicken. If sea ice did form at winter quarters, it would be held in by the Mackellar Islands, and results similar to those for lake ice described by Chamberlin and Salisbury* might be possible. When the ice has once formed, a further lowering of temperature will cause contraction; and the water will then rise along the contracted margins and immediately freeze. If the water is shallow, ice may become attached to rocks and boulders on the bottom. A subsequent rise in temperature causes the ice to expand, and the marginal layers, with their burden of enclosed boulders, may be pushed some distance up the shore; final melting will then leave a bank of boulders. It is possible that similar action has contributed to the formation of the "lower moraines" on Cape Denison.

6. *Nature of the Rock.*—Here, as usual, the hard resistant nature of the rock is important. Foliation planes and cross jointing, and the junction planes of the gneiss with the amphibolites have facilitated frost action. The amphibolites are usually softer than the grey granodiorite gneiss, and in consequence there are frequent depressions due to this fact. In one instance (Plate XVI., fig. 1) the reverse is true, and the dyke rock appears as a low thin wall. The detailed structures and compositions are discussed in a subsequent chapter.

ORIGIN OF THE VALLEYS.

The valleys above mentioned may have resulted from—

(*a*) The travel of the main ice sheet.
(*b*) Valley glaciers existing after the partial recession of the ice sheet.
(*c*) Thaw water action.
(*d*) Wind action.
(*e*) Pre-glacial strike valleys.

(*a*) The ice sheet has certainly been more extensive. Assuming that the ice sheet does erode its under surface in its forward movement, we naturally expect valleys to be carved approximately parallel to the direction of travel; but still differential movements are known to exist in a large ice sheet, and a small valley depression diverging 45° might result from such. In the present case, the four parallel valleys would require four different parallel sets of differential movements. This does not seem possible when we realise that we are dealing with a very small area only three-quarters of a mile broad.

(*b*) The glacier rises very steeply to the south of the rocks, approximately 1,000ft. in three miles and 1,500ft. in five and a half miles. The valleys are in the direction of greatest slope, and hence the formation of these valleys by subsidiary valley glaciers is quite possible. It is to be noted that three of the four valleys now contain ice permanently. In one case the ice was under observation for nine months and no movement capable of measurement took place. The fourth and ice-free valley has the steepest grade, and the sides are straight and in places steep, and, in a general way, indicate glacial movement in the direction on the valleys. The valley walls which slope with the dip are rounded and smooth, while those which slope against the dip are torn up and ploughed very rough. Morainic material is in one case distributed laterally along the walls, while the glacier ice itself is partly coloured by the presence of the subglacial material. If valley glaciers of this type exist, a set of minor ice movements are introduced subsequent to, and in a different direction from, the movements which produce the striæ observed N. 32° W. We were unable to pick up any trace of a second set of striæ, while in the lower part of one valley, where it opens out to a broad area, striæ can be seen trending in the constant direction N. 32° W.

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* "Earth Processes," p. 389.

The upper limit of the subglacial material of the ice sheet (marked by a dotted line on the locality plan) descends to lower levels at the head of valleys, suggesting that morainic material has been pushed further on in the direction of the valleys. Hence in spite of the absence of the second set of striæ, secondary minor movements of the valley glacier type are suggested. Such movement is negligible at the present time. A combination of (*a*) and (*b*) may probably produce the present result.

(*c*) Thaw Water Action.—This is a possibility that suggests itself immediately to one that has not visited the area. As above stated, thaw water action is, on the whole, feeble. The lakes are thawed out only for two or three weeks during the year. The character of the valleys is markedly not that produced by water streams.

(*d*) Wind Action.—The constant direction of the wind corresponds with the direction of the valleys, and this fact suggests wind-scoured depressions. The unsymmetrical and varying slopes on the valley walls are hardly consistent with the hypothesis, as the rock is of uniform hardness. Further, the undercutting, which is so characteristic of wind erosion, is, in the main, absent. An odd boulder shows wind erosion, but only in one small spot *in situ* did we observe undercutting. The rocks are remarkably fresh and unweathered, and the lapse of time since their uncovering cannot be great, and cannot be sufficient for wind excavation of the valleys.

(*e*) Pre-glacial Strike Valleys.—This theory will be accepted if all other possibilities are rejected. At present the short shallow valleys possess nothing that suggests water action. All such traces might disappear in the subsequent modification of the valleys during glaciation.

MORAINES.

Not only is our small area sprinkled with erratics, but also well marked moraines have been left by the retreating ice front in more or less parallel banks. These moraines are entirely the product of the basal load of the glacier. No surficial or interglacial material is present in the terminal section.

The ice front of the glacier rises very steeply to the south, and, for a vertical thickness of 40ft. above the rock floor, the ice is coloured brown by the presence of subglacial rock detritus (Plate XXXI., fig. 1). Similarly to the east and the west of Cape Denison, whenever the ice cliffs rest on a rock basement, brown-coloured ice could be seen for estimated thickness of 15ft. or 20ft. (Plate XIV., fig. 2). The ice sheet, therefore, has at this point eroded the underlying surface. In this connection it is interesting to recall the observation of a sledge party, 20 miles to the east, to the effect that rock outcrops at this distance away are found to be nearly devoid of morainic material, though the ice sheet is continuous and unbroken. A paucity of erratics has also been noted by Sir Douglas Mawson at Cape Hunter, nine miles west of Cape Denison. The area of abundant glacial debris is, therefore, limited in Commonwealth Bay.

The subglacial material (Plate XXX., fig. 1) consists of fine rock meal, grit, pebbles, and boulders, some of the latter weighing many tons. For the greater part of the year it is all part of a hard-frozen zone, but the summer thaw loosens a good deal of surface material. The yearly ablation also liberates a certain amount. The finer material is, as above stated, swept away by the winds, and no glacial soil or gravel, except in isolated cases, can remain exposed. The exposed surface thus presents an aggregate of boulders of all sizes and shapes.

The moraines are, for the most part, thickly banked up in lines parallel and near to the glacial front. They contain a great variety of rocks which are not found *in situ*, and are, therefore, known to exist hidden beneath the ice cap. Among these rock types are crystalline limestones, lime silicate schists, sandstones and quartzites, granites, dolerites, vein and pegmatitic material, and schists and gneisses in great variety (Plate XIX., fig. 2). In general there is a great similarity between many of our specimens and those reported from the Ross Sea area by the Scott and Shackleton expeditions.

In the field it was found convenient to recognise an " upper moraine " and a " lower moraine." The " upper moraines " are true moraines, formed in the manner indicated above. It is the usual type of deposit with many of the stones much worn, though not often well rounded like river pebbles. Some look like rock chips with the salient angles and edges worn off. Many are subangular with plane and bevelled faces, and a small percentage (possibly ½ per cent.) are striated. The " lower moraines " are not strictly moraines at all. They do not occur above the 40ft. contour level and contain a very large percentage of local rock.

The abundant variety of rock types on the " upper moraines " makes them very different from the " lower moraines." In the latter the boulders are more rounded (Plate XIX., fig. 1), though still not altogether like river or marine boulders; many have plane, bevelled, gouged, and polished faces, but very few are striated. Further, some degree of sorting into sizes seems to have been accomplished. Some banks are dominated by boulders averaging one foot in diameter; while others consist, in the main, of pebbles about 3in. in diameter. The pebbles are, on the whole, coarse; but fine gravel and sand are always found when one turns the boulders over. The " lower moraines " are found in banks and bars which are parallel to the coast, and which follow, more or less, all the indentations of the contour. They are well seen in the lower parts of the valleys, and in one case three moraine bars appear in succession between the 40ft. level and sea level, producing a terraced appearance. In the panoramic view of Cape Denison looking east (Plate XXX., fig. 2), the " lower moraine " has the general appearance of a beach deposit.

The presence of these " lower moraines " is, no doubt, associated with the presence of the zone of relatively polished rock in the peripheral area below the 40ft. contour level. It has been mentioned that this zone is represented on the Mackellar Islands, where Sir Douglas Mawson has also noticed the presence of patches of roughly-rounded boulders of local varieties of gneiss which are similar to those on the " lower moraines " on the mainland.

There is no doubt that some of the boulders have been glaciated as well as water worn; but the abundance of local rock indicates a local origin. Their relation to the contours and to the outline of the coast is evidence of a marine origin. The grading into sizes must have been accomplished by sea water, though shore ice may have assisted to bank the material up into terraces. They probably represent glacial debris which has been subjected to wave erosion and which has become largely diluted with the local detritus produced in the ordinary course of marine erosion. They are the equivalent of the raised beaches in normal climates, and, therefore, indicate, like the zone of polished rock, a recent, slight relative uplift.

The beach origin of the " lower moraines " is confirmed by the finding in them of a small piece of grit containing shells. This single specimen (No. 702) was found close by the hut and has been examined by Mr. F. Chapman, A.L.S., Palaeontologist to the National Museum, Melbourne. Mr. Chapman has also examined samples of the sands obtained from both the typical moraines and the " lower moraines." His reports are now added.

NOTE ON A CONSOLIDATED BEACH SAND FROM CAPE DENISON.

By F. Chapman, A.L.S.

Macroscopic Appearance.—The rock is of a grey colour, with a roughened weathered surface (Plate XIII., figs. 1 and 2). It measures about 5·5cm. by 4·3cm. The texture is coarse and gritty, and closely resembles a consolidated beach sand such as may be met with in all latitudes under favourable conditions. To my own knowledge the nearest rock in appearance to this is a specimen I collected many years ago from the coast of Ilfracombe, in Devonshire. In that instance the rock was formed by the concreting action of percolating water charged with dissolved CO_2 reacting on the shelly particles of the beach. The present specimen shows strong effervescence with HCl.

Microscopic Characters.—In thin slices under a moderate power of the microscope (2in. obj.) the rock is seen to consist mainly of angular quartz grains intermixed with a few particles of igneous rock, more or less basic, and with occasional twinned and zoned felspars. Brown palagonitic glass showing perlitic structure occurs in the rock, and also numerous crystals of augite. The average diameter of the larger grains is 0·4mm. (Plate XIII., fig. 3).

Organic Particles.—Remains of foraminifera tests are seen; and one fine cross section of a milioline, of the *Miliolina subrotunda* type, is present. A fragment of an indeterminate coral appears in the hand specimen, and its examination by means of the micro slide leaves no room for doubt as to its relationship to that group. The coenenchyma is cavernous and traversed by strong pillars, and there is abundant evidence of the "dark-line" structure of a recent coral. It appears to be an arborescent form (Plate XIII., fig. 4).

An echinoderm plate is seen in section, distinguished by its typical perforate character and calcitic structure.

Matrix.—This consists of a fine detrital dust and minutely crystalline calcareous cement. The larger fragments are generally evenly spaced out in the mass.

Conclusions.—The present specimen is a consolidated beach sand, consisting largely of cleanly broken particles of terrigenous material of the nature of basic and sub-acid igneous rocks, evidently derived from the immediate locality; these, together with littoral and coral zone organisms, are cemented in a matrix composed of a mixture of fine igneous rock detritus and calcareous deposited material.

NOTE ON MORAINIC MATERIAL, CAPE DENISON.

By F. Chapman, A.L.S.

Morainic Mud.—From Lower Moraines found underneath boulders. About 35ft. above sea level.

This consists of angular fragments and sand grains derived from hornblende gneiss and schists, with some material, probably from a granitic source. The fine washings contain numerous crystals of micaceous, pyroxenic, hornblendic, and felspathic minerals. No organic remains were noticed.

Morainic Detritus.—Sample from Upper Moraines, taken from the ice, about 120ft. above sea level, Commonwealth Bay.

Coarse and fine detritus of hornblende gneiss and granitic rocks containing pink and white felspars. Fine washings include numerous small crystals of ferro-magnesian silicates and felspars. No organic remains were seen.

CHAPTER III.

THE METAMORPHOSED DYKE SERIES OF CAPE DENISON.

1.—Nomenclature.

The nomenclature generally adopted in the following pages is that taught in the "Die Kristallinen Schiefer."* Grubenmann's treatise deals with schists and gneisses which have developed by the thermo-dynamical alteration of pre-existing rocks. He has told us what rocks belong to the crystalline schists, and in these the effects produced by the alterations completely determine the character of the rock.

Various meanings have been attached to the term "metamorphic rock," and we are in general agreement with the criticism of this term given by Crook†. Crook points out that Van Hise's use of the term is too broad, as it is made to include all rocks, and that there is no satisfactory definition of the term ; either it is made too incomplete or too comprehensive in its meaning, and he desires to exclude a group of metamorphic rocks from the fundamental rock classification into igneous, sedimentary, and metamorphic. The old group of metamorphic rocks is replaced by several groups, including a group of thermo-dynamically altered rocks which are unfused and unmodified by exudations. This group seems to correspond with the Kristallinen Schiefer. If we adopt this subdivision, are we to exclude the term "metamorphic" from our nomenclature ? We are inclined to think that the term is too deep rooted and too convenient to permit this. It is therefore necessary to state that in the following account of the metamorphic rocks of Adelie Land we use the term in the limited sense indicated in Grubenmann's work and adopted by Johnston and Niggli‡. We are dealing with rocks which come under the heading of the crystalline schists, and when we refer to a rock as metamorphic we imply that it falls into the group of the crystalline schists.

Its use in this way comes partly from the want of a general rock term for those members of the crystalline schists which possess a massive texture in contrast to the schistose or gneissic texture. The terms schist and gneiss are not fundamentally different, and the same processes produce the foliation of the gneissic granites and the foliation of the sedimentary gneisses. A gneiss can be looked upon as a schist with an imperfect schistose structure ; and should this structure become too insignificant to be noticeable, what shall we call the rock ? Sederholm§ has considered that it is impossible to give the term "gneiss" a limited meaning, and he believes that it must remain a comprehensive name with a very wide significance. We find that this wide significance may have real use, and we have used the term " gneiss " as a general rock name for members of the crystalline schists which have no special name and which may or may not possess a schistose structure ; for example, a certain rock has been styled pyroxene granulite by the Germans, pyroxene gneiss by the French, and a norite by the Indian Geological Survey. We do not use the term " pyroxene granulite " because the granulitic structure is a very common structure in almost all classes of the crystalline schists. We do not use the term " norite " because it is applied to a special variety of igneous rocks. We apply the term gneiss in each case, and distinguish as a plagioclase-pyroxene-gneiss, or a pyroxene-alkali-felspar-gneiss, in spite of the fact that no schistosity may be evident.

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* "Die Kristallinen Schiefer." U. Grubenmann, Berlin, vol. I., 1904, vol. II., 1907.

† "The Genetic Classification of Rocks and Ore Deposits," T. Crook, Min. Mag., vol. XVII., p. 69.

‡ "Principles Underlying Metamorphic Processes," Johnston & Niggli, Journ. Geol., vol. XXI., p. 481.

§ "Om granit och gneis," J. J. Sederholm, Eng. Summary, Bull. Com. Geol. Fin., No. 23, 1907, p. 109.

As we make large use of the term " amphibolite " we quote the following from L. Henzer * :—" By older writers a pure amphibole rock is occasionally called amphibolite, while the garnet-amphibolites, felspar-amphibolites, or zoisite-amphibolites were called amphibole schists, greenstone, hornfels, etc. According to Zirkel, the typical amphibolite consists only of hornblende. Chiefly through Rosenbusch the term has become firmly established in the literature in recent years. Rock types with amphibole as their main constituents (hornblende-schists or hornblende-fels and actinolite schists) are distinguished from the actual amphibolite whose mineral content is essentially hornblende and plagioclase, though the latter can be replaced partly or wholly by zoisite, epidote, garnet, or scapolite." This is the usage which has been adopted by Grubenmann and which gives the term amphibolite a precise chemical and mineralogical meaning.

The need of the general term, which we supply for ourselves in the term " gneiss," is evidenced in a paper published by Loewinson-Lessing† in 1905, which discusses the classification and nomenclature of the amphibole rocks belonging to the crystalline schists. In the study of the crystalline schists of the River Tagil, in the Middle Urals, Loewinson-Lessing was struck with the close connection between the schistose and massive members of the crystalline schists. He found massive schlieren in the midst of schistose rocks and argued that the term " schist " was scarcely fitting for the non-schistose rocks. But he meets his difficulty by introducing terms which emphasise the likeness of the massive types to igneous rocks—*e.g.*, paradiorite, amphibole, para-gabbro, etc. These terms obscure the observed close connection of these rocks with the crystalline schists. They unduly accentuate differences which have no genetic bearing and place them equivalent with characters which do have genetic meaning. But yet they are intended to limit and add precision to the term " amphibolite." An amphibolite, according to Loewinson-Lessing, is a rock whose essential constituent is amphibole alone. This violates the conclusion expressed in the preceding quotation from a paper to which Loewinson-Lessing makes no reference. A rock composed of amphibole and plagioclase is called " paradiorite " or " amphibole para-gabbro " if it has a massive structure, but if schistose, it is called "diorite gneiss" or "amphibole gabbro schist." If we accepted this nomenclature we should have to give the names "paradiorite" and "diorite gneiss" to two rocks of similar origin but with slight variation in structure. If quartz should be introduced into this rock by some metamorphic process the rock would become a "para-granodiorite" or a "granodiorite gneiss"; but we will show that such a rock has nothing whatever to do with granodiorite or its gneissic modification. It is obvious, therefore, that this nomenclature can have little value in any genetic study.

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* " Ein Beitrag zur Kenntnis der Eklogite und Amphibolite," Laura Hezner, Wien, 1903, p. 5.

† " Ueber Klassifikation und Nomenklatur der zur Formation der Kristallinischen Schiefer gehorigen Amphibolgesteine," von F. Loewinson-Lessing, Centralblatt Mineralogie Geologie, 1905, p. 407.

In the nomenclature that we have adopted we use the term "amphibolite schist" when the amphibolite has a marked schistose structure, the term "biotite amphibolite" when the hornblende is partly replaced by biotite, and the term "quartz amphibolite" when the amphibolite has been modified by the addition of quartz.

In our study rocks have been found to contain structures similar in appearance to the micrographic and micropegmatitic intergrowths that are formed by the crystallisation of a eutectic mixture in igneous rocks. In numerous instances this "micrographic" intergrowth has a direct metamorphic origin. Consequently, we have not used the term "micrographic" or "micropegmatitic," which may be conveniently retained for igneous structures. We have described the structure a diablastic structure.

2.—Field Characters.

The Cape Denison granodiorite gneiss is laminated by a rock type which appears as a series of parallel black bands of amphibolites and epidote biotite schists. It is a foliated rock type and its foliation is parallel to the trend of the bands as well as to the foliation of the gneiss. The cleavage planes are usually vertical. The bands are usually between 18in. and 2ft. wide, and being jet black in colour they present strong contrast to the grey gneiss on the bare rock floor. When the gneiss assumes a dark colour relations are less obvious. The junctions between the bands and the grey gneiss are typically sharp, well defined, and straight, and in general appearance they suggest the field relations of a system of parallel dykes which have intruded the gneiss.

One band may be continuous across the area, but more often it is broken. In the latter case the band wedges out and disappears for a while and then reappears some distance further along the strike. Sometimes a band opens out into a bulge and then occupies a width of 30ft. or more. A case was noted where a band which is continuous for some distance suddenly breaks off and does not reappear along the line of strike, while a band commences in a similarly sudden manner 40yds. due west. A white quartz vein starts from one broken end and runs toward the other, but it peters out before reaching it. One immediately suggests that this band has been faulted, and the fault fracture filled by quartz. But if all the bands were contemporaneously formed, such faulting is highly localised, as the next adjacent band on the east is continuous.

The bands are not uniformly spaced across the area. They may be 50yds. or 100yds. apart, or they may be separated by only a foot. Three bands close together can be seen on the valley floor in Plate XXII., fig. 1. In one case two bands appear to unite, but the surface rock is disturbed and the junction so fractured by frost that the observation is a little indefinite. A single band, however, may run out into a series of parallel threads which enclose layers of gneiss between them, and these threads may unite. Detached fragments of the black rock are sometimes observed to be completely enclosed in the gneiss. Such fragments are either in close proximity to a band or else replace the band in a discontinuous outcrop (fig. 2). These schlieren always possess a lenticular outline.

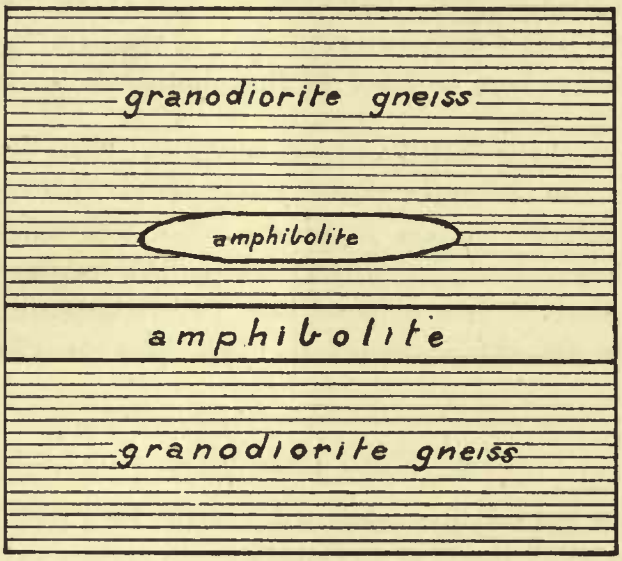

Fig. 2.

Diagrammatic Sketch showing a Lenticular "Inclusion" of Amphibolite Lying Close to and Parallel to the Main Dyke Channel.

In one example that was noted in both plan and section (fig. 3) the foliation of the gneiss is bent around it, *i.e.*, the foliation does not continue through both black and grey rocks indiscriminately, though the black rock is schistose itself. This example was about 6ft. long and about 1½ft. in diameter. These schlieren may be penetrated by quartz felspar veins.

The black rock is generally softer than the enclosing gneiss and yields more readily to the mechanical weathering. Consequently the bands frequently travel along slight depressions. In Plate XXII., fig. 1, where we have several bands close together, we find them on a valley floor. We often find that a band forms a gully-way. The reverse, however, is true in the case of a band which passes the memorial cross on Azimuth Hill. Here the band has been more resistant than the granodiorite gneiss and stands as a thin wall 3ft. above the level of the gneiss (Plate XVI., fig. 1). The latter is a fine-grained type and contains more mica than usual.

Green epidote and less commonly purple fluorite are often developed along the junction planes between the gneiss and the amphibolites. These minerals are also found along joint planes in both granodiorite gneiss and amphibolite. Small quartz segregation veins may be found in the bands, and these may carry excellent crystals of epidote 2½in. and 3in. in length.

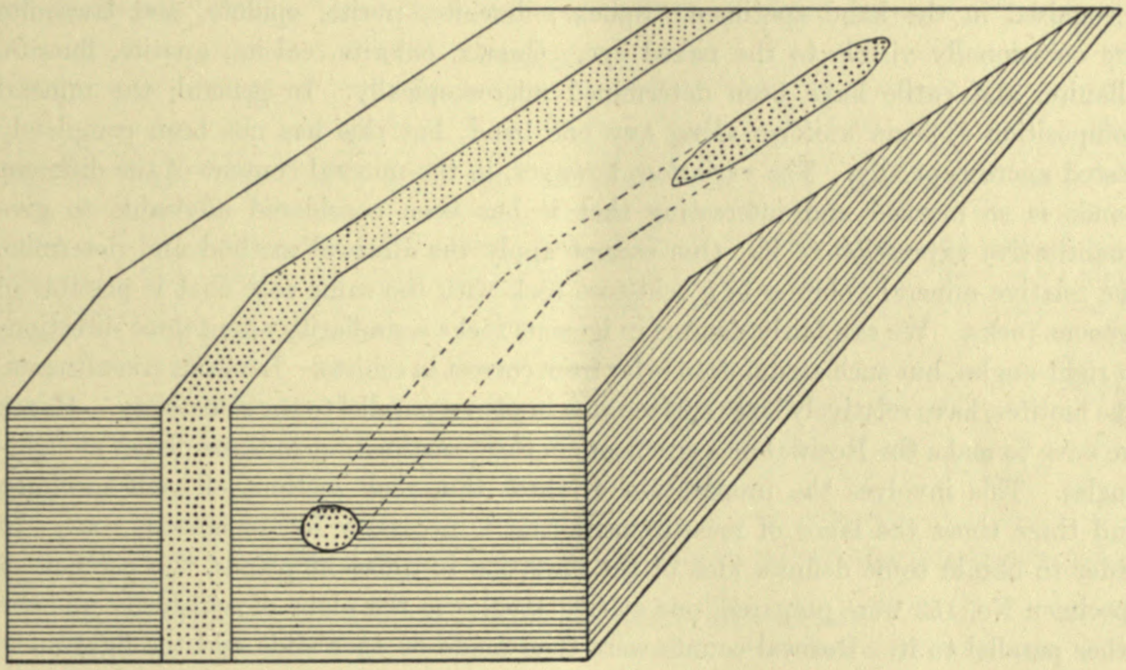

Fig. 3.

Diagrammatic Sketch showing a Lenticular "Inclusion" of Amphibolite which is seen Partly in Plan and Partly in Section.

In one instance (No. 629) where a band has opened into a bulge a number of inclusions of white, grey, and pink colour are found enclosed in the amphibolite. These inclusions appear across the whole outcrop, but are present in greatest numbers along the western side of the band. They are considered to be xenoliths and will receive full description later.

3.—Petrographical Characters.

The rock type presents great variation in texture, structure, and mineral content. The colour is usually jet black, more rarely grey black. The texture, in some examples, is highly schistose, and the dominating flaky constituent is either biotite or hornblende. In fine-grained types the texture becomes slaty schistose. In some examples the texture becomes approximately massive. Indeed, the texture may vary in a short distance from massive to schistose in one and the same band. The predominating structure is granoblastic, which, in the massive types, might be called gabbro structure. Sometimes there is a tendency to a nematoblastic (fibrous) structure and poikiloblastic and relic structures are also present.

Mineral Composition.

Hornblende, biotite, and felspar are the commonest mineral constituents that can be recognised in the hand specimen. Sphene, ilmenite, pyrite, epidote, and lawsonite are occasionally visible to the naked eye. Quartz, chlorite, calcite, apatite, fluorite, allanite, and rutile have been determined microscopically. In general, the mineral composition appears uniform along any one band, but this has not been completely tested microscopically. The variation, however, in the mineral content of the different bands is so marked and interesting that it has been considered advisable to give quantitative expression to it. One cannot apply the Rosiwal method and determine the relative mineral volumes in a schistose rock with the same ease that is possible in igneous rocks. We can fairly assume in igneous rocks a similarity along three directions at right-angles, but such assumption is far from correct in schists. Lamellar constituents, like biotites, have relatively large surface area in planes parallel to the schistosity. Hence we have to make the Rosiwal measurements in three sections cut in three planes at right-angles. This involves the preparation of three thin rock sections of each specimen and three times the labor of measurement that is necessary for an igneous rock. In order to obtain some definite idea of the variation in different planes, two sections of specimen No. 153 were prepared, one at right-angles to the plane of schistosity and the other parallel to it. Rosiwal counts were then made on each slide and the figures are given in Table 1. Biotite and hornblende increase their volume by one-third, the epidote increases in smaller proportion, while felspar decreases its volume by one-third. Notwithstanding these differences, it was considered that a relative quantitative expression of the mineral volumes would be obtained from a single section provided that each section of the rocks to be compared is cut in the same direction. The sections studied in each case are cut at right-angles to the plane of schistosity and typical examples selected for treatment. The figures obtained are sufficiently accurate to be serviceable in expressing the relative variation of the constituents in this suite of rocks of common origin and of more or less common history.

Later study of the crystalline schists from Stillwell Island and Cape Pigeon Rocks shows that the estimation of the mineral content from a single slide may be absolutely misleading in regard to the nature of the rock. Small specimens of gneiss—apparently uniform in the hand specimen—may contain considerable garnet in one part and none in another part. When, however, the rocks are of comparatively uniform mineral composition, as in the case of this dyke series, the results are useful.

The figures are given in Table 1, where each example represents a different band, and these are arranged in the order of outcrops met in traversing the area from west to east. No. 1 is the most westerly. The heading " felspar " includes all the colourless constituents—the clear albite, the cloudy felspar, quartz, and apatite, lawsonite, and calcite when the last three are not separately determined. Quartz is never abundant and nearly always very subordinate; as it is very difficult to distinguish it in all cases from the clear secondary felspar, very little is lost in value and a great saving in time is effected by reckoning it in with the felspar. Apatite, lawsonite, and calcite are separately measured when sufficiently abundant, otherwise their presence is indicated by p. The heading " iron ore " includes magnetite (or ilmenite) and pyrite as pyrite is very sporadic and occasional. " Mica " includes biotite and chlorite, which are frequently intergrown.

TABLE 1.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Field No.	153	153	5	412	720	630	629	631	637	634	634A	635	9
Felspar ...	46·1	31·2	32·3	25·8	12·4	54·5	27·3	28·5	35·3	31·8	13·9	27·4	23·1
Mica	35·9	48·8	7·8	33·0	16·8	15·9	1·2	7·5	4·2	10·8	5·6	8·0	10·7
Hornblende	2·5	4·0	47·6	36·1	60·3	19·8	69·7	61·8	49·8	56·3	77·3	56·3	61·8
Epidote ..	8·2	9·5	6·8	3·0	1·9	5·0	·5	·3	·6	·7	·2	·7	1·8
Sphene ...	3·2	2·2	3·5	—	1·5	3·2	·9	1·4	4·1	—	—	—	2·6
Iron Ore ..	3·0	3·4	·6	p.	·3	·6	·4	·4	6·0	·7	1·5	·7	
Apatite ..	1·4	·9	1·4	p.	·1	1·0	p.	·1	p.	p.	—	—	p.
Lawsonite.	—	—	p.	1·5	6·7	—	p.		—	p.	1·5	3·0	—
Calcite ...	—	—	—	·6	—	p.	p.	—	—	—	—	—	—

1. A fine-grained micaceous type which has proved more resistant to weathering than the surrounding granodiorite gneiss.

2. The same rock as 1, but measured in a section parallel to the schistosity.

3. An example that appears as a system of irregular schlieren rather than as a distinct band.

4. A normal band which contained irregular quartz segregation veins carrying large epidote crystals. The quartz in-filling is subsequent to the band and the foliation.

5. A well-defined band from which No. 720 is the single specimen in the collection.

6. An abnormal band containing one of the remarkable biotitic patches. The sample was collected as the " normal " part of the band, a few feet away from biotite clot.

7. A typical massive type taken from the band which contains the xenolith.

8. Normal band.

9. A sample of a schliere of dark rock in the granodiorite gneiss. The schliere is impregnated with felspar-quartz veins which have participated in the folding and are contorted.

10. Normal band.

11. A band situated between No. 10 and No. 12. These three bands lie very close together and are not separated by more than a yard from each other.

12. Normal band.

13. Massive amphibolite which is here inserted for comparison. It grades out in parts into felspathic gneiss and in part into pure hornblendic rocks.

The table indicates that we have three main varieties in this suite of rocks—

1. Rocks containing dominant biotite (*e.g.*, No. 153, which will be described as an epidote biotite schist).
2. Rocks containing biotite and hornblende in approximately equal proportions (*e.g.*, Nos. 412, 630, the biotite amphibolites).
3. Rocks containing dominant hornblende (*e.g.*, Nos. 629, 631, etc., the amphibolites).

We can notice in general that the biotite-rich varieties belong to the western side of Cape Denison and that the hornblende-rich varieties belong to the eastern side. These two groups are separated geographically, with the exception of No. 5, by bands in which biotite and hornblende are both important. The exception, No. 5, loses its importance when we reflect that it is not an example of a typical band. This uniform mineral variation will be considered later to be a reflection of the variation in chemical composition. The geographical nature of these variations is important, and can have but two possible explanations. The explanation may be a metamorphic one, and we may consider the reason to be a uniformly varying set of metamorphic conditions across Cape Denison combined with a uniform degree of migration of material corresponding with differences in chemical composition. The detailed examination indicates that we really get considerable variation in the conditions in localised patches, and thus scarcely supports this explanation. The alternative consists in regarding the whole as a differentiated series of primary basic dykes. In either case it does signify that we are not dealing with bands that have been repeated by folding.

With a high percentage of mica there is always found a high percentage of epidote. The only important exception to this rule is again No. 5. No. 720 is a partial exception, but a relatively low percentage of epidote is compensated by a high percentage of hydrous lime silicate, lawsonite. Nos. 720 and 634A possess a percentage of ferromagnesian minerals very considerably above the average while the felspar percentage is correspondingly low. It is possible that they are chance specimens which are not strictly normal of the bands they represent. Unfortunately, there is no systematic set of specimens collected for the purpose of studying the longitudinal variation in any particular band. Only in exceptional cases is the variation noticeable in the hand specimen. In cases where more than one specimen has been examined from one band some degree of variation is always noticeable.

The table renders it evident that the majority of the examples are rich in sphene, but the accessories show considerable variation. Apatite is relatively high in some cases and practically absent in others. The iron ores show much greater variation, and vary from 6 per cent. to instances where it is almost negligible. The complete discussion of this table of mineral constituents must await the presentation of the microscopical and chemical characters.

Microscopical Characters.

No. 153.—This rock is rather fine grained and schistose, but it is not so particularly fissile as some of the hornblende varieties. The glint of the mica is obvious on the cleavage faces. In thin section the constituents conform to a linear arrangement and produce the crystallisation schistosity (Plate I., fig. 3). The biotite is strongly pleochroic in sections showing cleavage from a light straw to a deep brown colour; it is reddish brown in basal sections. Pleochroic haloes are sometimes found around inclusions which appear to be sphene. Hornblende is sometimes included in the biotite and sometimes the biotite in the hornblende. The felspar appears in rounded and indented grains. A few scattered grains only are clouded. It is generally perfectly clear and transparent, and there seem to be two types of plagioclase, and possibly also orthoclase. The bulk of the felspar is untwinned. A few grains with lamellar twinning give values between 20° and 27° for the extinction angle. This is best interpreted as andesine. From ground-up powder of the rock refractive index was found to be less than 1·542 in some cases, but mostly between 1·542 and 1·551. In the section the refractive index was rarely found below that of Canada balsam. Hence the bulk is probably andesine with a few grains of either orthoclase or albite. Quartz is present as a very minor constituent and has an appearance very similar to the clear felspar. It can only be distinguished with certainty from the felspar by the use of convergent light, and considerable search is required to find a uniaxial figure. The hornblende is definite and strongly pleochroic. Its colour scheme is—X, greenish yellow; Y, bright green; Z, bluish green. It has an extinction up to 15° in prismatic sections. Sphene, exceeding 3 per cent., is conspicuous in wedge-shaped crystals and in grains. It conforms to the schistosity, and frequently encloses an idioblastic crystal of magnetite. It is also occasionally associated with rutile. Epidote (8-9 per cent.) is more abundant in this rock than in any other member of the series except when found in segregations. It appears in pleochroic lemon-yellow crystals, commonly idioblastic, and shows the brilliant polarisation colours of the third order. It does not possess the same dark border of colour as sphene, and the polarisation colour of sphene usually reaches the high order whites. In rare cases it is found intergrown with zoisite (or clinozoisite). Colourless apatite is a notable accessory, and its crystals are at times comparable in size to the sphene grains. Magnetite is present in the same proportion as sphene and is sometimes idioblastic, apart from the sphene enclosures. Cubes of pyrite are very sporadic. Fluorite is not infrequently found in irregular isotropic blue grains, but it may be intergrown with the biotite after the manner of chlorite. No. 153 may be called an epidote biotite schist.

No. 5.—This specimen has been referred to as abnormal. It possesses a slightly coarser grain size than the average. The crystallisation schistosity is less marked and there is a tendency to a massive texture. The structure at the same time becomes more granoblastic. Apatite, epidote, and sphene especially participate in the increased grain size and now appear in grains comparable in size with the felspar and hornblende crystals. The percentage of epidote is noticeably high in comparison with the mica content, and we can recall a field note stating that the precise locality of No. 5 is especially rich in epidote. Epidote and, to a less degree, fluorite are especially abundant in seams and joint planes at this point. A further characteristic of the sample is the replacement of biotite by the green pleochroic chlorite which frequently gives the ultra blue polarisations colour. The chlorite plates are usually associated with and penetrated poikiloblastically by well-formed epidote, clear felspar (which looks like quartz), and stray grains of magnetite. The green hornblende is abundant and idioblastic in sections, showing two cleavages. The terminal faces of prismatic sections are not developed. At times the hornblende is streaked and fringed by much paler hornblende. Such hornblende becomes very distinct between crossed nicols in virtue of its bright interference colours. Chlorite is associated in some parts with the hornblende in a way suggesting that the chlorite gradually passes into hornblende. In other parts there is a transition between epidote and hornblende. The greater part of the felspar is cloudy and saussuritised. Arising out of the saussuritised part the secondary plagioclase can be seen. Epidote may be found in the saussuritised mass as well as magnetite, scales of hematite, and micaceous products. In the same connection radial aggregates of a fibrous cloudy mineral are found with very low refraction, double refraction about the same as quartz and oblique extinction with a small extinction angle. This is probably stilbite, one of the zeolite group, which is much better developed in the next slide. Sphene possesses rather a deeper clove-brown colour than usual, and is almost free from the magnetite core. No. 5 may be called an amphibolite.

When the joint planes, which are lined with epidote, are exposed by weathering, they form a rock wall brilliantly green in colour. Some of the hand specimens are faced with the green epidote about 1mm. thick. In these specimens the rock can be seen to become very distinctly richer in epidote as the face of the joint plane is approached. There is a segregation towards a plane in this case, whereas in a subsequent example, the epidosite in the band No. 629, the segregation is apparently towards a centre.

Some of the joint planes are characterised not so much by the green epidote or by fluorite as by a radiate, fibrous mineral of pinkish-white colour. A thin section was cut as close as possible to the face of one of these joint planes in order to include the fibrous mineral, and has been found to be very interesting. Not only are the relation of epidote, chlorite, and hornblende clearer than in the preceding slide, but stilbite, fluorite, and lawsonite are present. The radiating fibrous aggregates are prominent in the section and the mineral is mostly clear and colourless, though cloudy in part. Its refractive index is less than Canada balsam, and its polarisation colours are a little higher than those of felspar. It has an extinction angle up to 10°, and, as the prism axis is the direction of the fastest ray, it can be determined as stilbite. Grains of fluorite are not infrequent. Sometimes they show a trace of blue colour, and they may be crowded with minute needles of a green mineral with oblique extinction, probably pale hornblende. The development of chlorite and epidote from hornblende is more noticeable. The green hornblende first passes into colourless hornblende, which may be replaced by an aggregate of epidote and chlorite. Grains of fluorite may be found in these aggregates. The hornblende also undergoes a change through colourless hornblende, with oblique extinction, into the brightly polarising lawsonite, with its straight extinction. Aggregates of lawsonite may fringe the radial groups of stilbite. Some of the lawsonite aggregates resemble scapolite in appearance, but the refractive index is too high, and wherever an interference figure is obtained it is biaxial in character. There is here, perhaps, more clear felspar than in the normal slide. The refractive index of this clear felspar is sometimes above and sometimes below Canada balsam, but it is always very close to it. The clear felspar, therefore, belongs to the albite end of the lime soda series.

No. 412.—In this case the hornblende and biotite exist in practically equal proportions. There is a well-developed schistosity, and the mica flakes give a bright sheen to the cleavage surface. The grain size is about normal and a little larger than that of No. 153. In thin section (Plate I., fig. 2) the hornblende and biotite possess the usual characteristics. The greater proportion of the felspar is quite clear and transparent, the lesser portion is saussuritised as in No. 5. Calcite is present in coarse granular crystals, and has probably developed in the alteration of the felspar. Epidote is very distinct in pleochroic crystals and may be intergrown with the biotite or with the hornblende. In both cases it may exert its crystal form against the hornblende and the biotite. A small percentage of lawsonite is recorded in the rock, and it is usually interlaminated between the cleavage veins of the biotite. It might be mistaken for colourless epidote, but a difference is obvious when the two minerals are brought into the same field of view. Lawsonite attains its best development in Nos. 720 and 635, and its characters will be fully defined from those sections. Occasionally purple fluorite is threaded with the biotite in the same manner as in No. 153. Sphene is practically absent, and there are only very few particles of iron ore and crystals of apatite. No. 412 may be called a biotite amphibolite schist.

No. 720.—The example is a lustrous schistose rock in which hornblende, mica, and some colourless felspar or lawsonite are visible to the naked eye. The mica has a golden-brown colour.

In thin section (Plate I., fig. 6) the hornblende has its normal appearance, but the mica content consists of intergrown biotite and chlorite in which the latter is dominant. The biotite tends towards a biscuit-brown colour that is best developed in No. 635, and it is pleochroic from this brown colour almost to colourless. The chlorite is also pleochroic through shades of pale green to colourless. Hence, in some positions of the polariser, the intergrowth of biotite and chlorite may look homogeneous. The composite character is readily observed by rotating the stage or by crossing the nicols. The chlorite possesses bright ultra blue polarisation colours, and the biotite shows brilliant second and third order colours. The "felspar" percentage consists entirely of cloudy brightly polarising aggregates. Clear felspar is absent. The association of saussuritised felspar and lawsonite seems to be very characteristic. The lawsonite is abundant and may be intergrown with the mica, less frequently with hornblende, or it may appear in laths with parallel arrangement contributing to the schistosity of the rock. When best developed the laths are clear and colourless with prominent parallel cleavage. Sometimes it is a little cloudy and some lawsonite areas enclose pieces of saussurite, thereby indicating the connection. The lobate outline is conspicuous when intergrown with biotite, but the laths mostly possess straight sides when intergrown with hornblende. A slight lobateness is sometimes detected against the hornblende, but is never prominent. A section has been noted where the end portions of a lawsonite crystal are bounded by hornblende crystals, while the middle third abuts against chlorite. The junction against the hornblende is linear at both ends, but the middle portion is curved against the chlorite. Granular epidote is present and can be distinguished from the lawsonite by its colour and pleochroism. Sphene is a moderately abundant accessory. The rock is the best example obtained *in situ* of a lawsonite amphibolite.

No. 630.—This sample comes from one of the thicker outcrops. The outcrop is remarkable in containing a patch of rock which appears to be mostly biotite in the hand specimen. The difference noticed underfoot in passing from the ordinary rock to the biotite is similar to the difference between a pavement and a carpet. The hand specimen is, perhaps, not so dark coloured as the other examples. The measured section is cut at right angles to the plane of schistosity but not at right angles to the direction of stretching. This, however, has not affected the general character of the individual.

The mineral composition shows an extraordinary percentage of the colourless components, felspar and quartz, but examination shows that there is much more quartz than usual. The quartz is occasionally in large grains, clear, and often without wavy extinction, and so grouped as to suggest segregation or absorption of secondary silica into the rock. This quartz gives the rock an abnormal silica percentage. The clear felspar is about equal in amount to the saussuritised felspar, but their distribution is quite irregular. Clear felspar is dominant in some parts of the slide and saussuritised felspar in other parts. Some comparatively clear felspar with broad lamellæ can be found. Extinction angles up to 37° can be measured, and labradorite is therefore present. Sometimes the calcic plagioclase is partly saussuritised, and the saussuritisation is more intense along one alternate set of lamellæ. Such examples suggest that it is a relic felspar. Apart from this calcic plagioclase is another plagioclase, always in clear rounded interlocking grain, which is interpreted as an oligoclase or andesine. The biotite is curious. Some biotites are pleochroic in cross sections from a light-straw colour to a dark brown, while other biotite crystals are pleochroic from a pale-greenish yellow to a deep-emerald green. That there is no great difference between the brown and green varieties is shown by the way the brown and green may be laminated in one and the same crystal. The polarisation colours of the green part are too high for green chlorite. In some parts, when in association with the cloudy felspar, the green mica is a little paler and more like chlorite. Here lenticles showing the ultra blue polarisation colour may be found. Epidote is associated with the green biotite in the same way as it is associated with chlorite in No. 5. It seems that we have here the change from chlorite to biotite during the process of recrystallisation. The chlorite passes over into biotite with the absorption of alkali first by deepening its green colour and later by changing colour to brown. The hornblende is normal. Epidote, sphene, and apatite are relatively abundant. Occasionally the grains of epidote are found with a nucleus of calcite and magnetite. The calcite has been formed from the decomposition of a primary mineral, and at this centre of recrystallisation there has been more calcium and iron available than actually necessary for the production of epidote. Epidote sometimes forms a pale border to a red-brown mineral, pleochroic with high refractive index and high double refraction. By comparison with other occurrences from this area we record this mineral as allanite. The rock may be called a quartz biotite amphibolite.

No. 629.—This specimen is a normal example of the hornblende rich varieties, and it is especially interesting as it comes from the band which contains the xenoliths. It contains the second highest percentage of hornblende, almost 70 per cent., in the series. It is one of the massive types, and white felspar and dark hornblende are the only constituents which are macroscopically distinguishable. As is usual with the massive varieties the structure becomes granoblastic (Plate I., fig. 1), and the average absolute grain size is approximately ·22mm. The hornblende is green with the bluish-green tint parallel to Z. As in No. 5, the hornblende is sometimes bordered and streaked with paler coloured hornblende. Prism faces are well developed, but prismatic sections always have a broken and ragged appearance. Sometimes the hornblende forms a skeletal framework for felspar and quartz, and then a sieve structure (siebstructur) appears. Like the hornblende, the felspar is in granular individuals. The majority of it is clear and transparent, and there are two types present. Some clear calcic felspar is found with an extinction of 35° measured from the trace of the broad lamellæ and is labradorite. The lamellæ of the felspar are often confused and intermittent and discrimination is difficult. A more sodic felspar is present which has a refractive index less than 1·551, and sometimes greater than and sometimes less than 1·538. This felspar is, therefore, becoming albitic. A quantity of the saussuritised felspar is present, and the secondary clear felspar can be seen arising from the turbid mass. Green chlorite appears in occasional skeletal plates showing the ultra-blue colour. It shows a transition to biotite. Sphene, with its magnetite core, is a common accessory. Epidote and pyrite are sparsely scattered through the rock. Lawsonite appears in microscopic veins in some sections. This section is made from a specimen taken from the centre of the outcrop. Sections made from specimens containing the xenoliths at the side of the exposure show more lawsonite. These lawsonite veins are sometimes composite (Plate I., fig. 5). There may be an epidote lining on the walls with lawsonite in the centre, or there may be lawsonite on the walls with calcite in the middle. The abnormally high percentage of hornblende and the low mica percentage are possibly to be associated with the patches of epidosite and chlorite which were noted here. The rock is an amphibolite.

No. 631.—There is another example of the rocks with dominant hornblende. Though the mica percentage is small the crystallisation schistosity is well marked. The granoblastic structure is evident. The felspar is nearly all clear and transparent and the proportion of saussurite is small. Occasional grains of quartz may be found. The hornblende conforms to the crystallisation schistosity and some crystals enclose felspar and blebs of quartz in a typically sieve-like manner. Brown biotite and sphene are normal. Magnetite is scarce but in large grains bordered with sphene. Some include prismatic sections of red-brown rutile. Minute crystals of apatite are enclosed in all other minerals and lawsonite is rarely intergrown with biotite. The rock is an amphibolite.

No. 637.—This example possesses weak schistosity and approaches a massive texture. Strings of white material can be seen in the hand specimen conforming to the schistosity. The measured section is not quite normal to the schistosity, and this is a factor in producing a slightly higher felspar percentage than is usual. Further, the example is obtained from a schliere impregnated with felspar-quartz veins, and it is likely that some of the visible white material is the same as in the veins. This would also raise the felspar percentage above the normal, and this appears confirmed by the presence of large grains of quartz in the section. The rock is granoblastic and very little saussuritised felspar is present—it is nearly all secondary clear felspar. The hornblende percentage decreases with the increased felspar percentage, but still the similarity of this rock to other examples is very obvious. The hornblende colour is normal, except in an isolated grain which gives bright blue pleochroism, indicating a tendency to the formation of glaucophane. This is interesting, as lawsonite has been looked upon as a frequent constituent of the glaucophane schists. Brown biotite is present in skeletal plates penetrated poikiloblastically by large crystals of sphene, magnetite, epidote, and felspar. The biotite appears in patches throughout the rock. Epidote is in small quantities, but the grains included in the biotite are well developed. Sphene is more abundant in this case than in other members of the series, though its average grain size is not so large. The core of magnetite is prominent and may be idioblastic. The magnetite as well as the sphene attains its maximum percentage here. The magnetite crystals are frequently idioblastic, and may be so large that we only get a thin veneer of sphene on them, and the sphene rim may not be continuous around their circumference. Minute apatites are present. The rock is an amphibolite.

No. 634.—In this example some degree of schistosity is produced by a parallel arrangement of hornblende prisms. Such arrangement is almost perfect in an adjacent band, No. 633, which is exceedingly fissile. No. 634 is granoblastic, and the abundant rounded and embayed grains of clear plagioclase enhance this character. Though the lamellar twinning is not well developed, some crystals with broad lamellæ can be found to give an extinction of 36°, indicating labradorite. The second sodic plagioclase is again present, and very occasional quartz grains can be found. The hornblende is normal but with more indented outline than in No. 635. The biotite is brown, and rarely intergrown with lawsonite, as the latter is very scarce. The iron ore consists of scattered grains of magnetite and pyrite. Sphene is absent. The rock is an amphibolite schist.

No. 634A.—This is a highly schistose specimen with abundant hornblende. Glistening mica with a light golden-brown colour is noticeable on the schist surface. The very large percentage of hornblende is the striking feature of this rock, and in section possesses the usual characters. The felspar is mostly cloudy and saussuritised, and only occasionally does a clear grain arise from it. The small amount of clear felspar in this rock is in contrast to the large amount of clear felspar in the neighbouring dyke, No. 634, a yard or so away from it. The mica consists of intergrown biotite and chlorite, of which the former is more abundant. The biotite possesses the same curious brown colour as in Nos. 720 and 635. Lawsonite appears in the same manner as in No. 720. The iron ore consists of magnetite and pyrite with some reddish hematite. The rock may be called a lawsonite amphibolite schist.

No. 635.—This example is a typical one with the parallel arrangement of hornblende crystals. The hornblende is the most abundant mineral and is developed in long prisms. Like No. 634A, the felspar is in strong contrast to No. 634, where it is mostly clear, while here it is nearly all saussuritised. Occasional clear fragments arise among the saussurite products. Grains of quartz, epidote, and mica can be distinguished in the decomposed mass. The biotite is not abundant and contributes little to the schistosity of the rock. Its colour is not quite normal. Basal sections possess a biscuit brown colour, and cross sections are pleochroic from reddish brown to colourless. Consequently the biotite possesses a curious bleached appearance. Lawsonite is well developed and reaches 3 per cent., and was identified in this section before the preparation of the thin sections of Nos. 720 and 634A. This colourless mineral is frequently found in parallel growth with the biotite (Plate I., fig. 4). Sometimes it is so developed after this manner that the biotite appears to be merely threaded in along its cleavage planes. Its form is usually lobated, and the biotite plates, in consequence, bend around its contour. Its cleavage is well developed and parallel to the elongation of the crystal and the cleavage of the biotite. Apart from its association with biotite, it may be found in grains among the saussuritised masses, and it also appears in small microscopic segregation veins. The outline of the sections is frequently granular, but in the veins it may be rectangular, and these show second order polarisation colours. Some sections, with low polarisation colours, have a distinct tendency to a rhombic outline. Wherever the cleavage or crystalline form is observable the mineral is found to have straight extinction. Further, its biaxial character can be verified, and hence it is orthorhombic. Its optical character is positive. Refractive index is high, higher than biotite and hornblende with which it appears in contact. The birefringence is high, and second and third order colours are seen. Some sections, however, possess quite low first order colours, indicating that two of the three principal refractive indices are not much different. These characters have fixed the identification as lawsonite. The lawsonite is not unlike a colourless epidote in appearance, but the latter would not have uniform straight extinction. Besides, epidote is present in isolated pleochroic grains of pale yellow colour and may be compared with lawsonite in the same field of view. The iron ore consists of scattered grains of magnetite and pyrite. Sphene is practically absent, and apatite is found in occasional needles. No. 635 is a lawsonite amphibolite schist.

Summary of Microscopical Characters.

The dominating constituent throughout the series is the dark-coloured ferromagnesian mineral, either biotite or hornblende, or both. The biotite is most important in the mica schists and the hornblende is most important in the amphibolites. The biotite is fresh and clear, and the Z colour is normally brown, varying to a reddish brown. In exceptional cases it is green, and both types may be found in the one section. Indeed, both types may appear in one and the same crystal, and the green biotite appears to be a transition stage between green chlorite and brown biotite. The micaceous constituent, in two of the described examples, is green chlorite. The chlorite plates always, and the biotite sometimes, present a poikiloblastic structure. The included minerals are epidote, felspar, sphene, and magnetite. Pleochroic haloes may surround inclusions in biotite.

The green hornblende is also fresh and clear. It is characteristically bluish green in the Z direction, indicating an admixture of the glaucophane molecule, and in one case a bright-blue grain of glaucophane appeared. More commonly there are streaks and fringes of pale hornblende through the more deeply coloured hornblende. Inclusions are not abundant in the hornblende. Sometimes rounded blebs of quartz and felspar produce the sieve structure. The prism and clino pinacoid faces are the best developed, and cross sections with two cleavages may be idioblastic. At times chlorite and epidote seem to develop from the hornblende.

In contrast to the fresh biotite and hornblende is the felspar, which may be quite turbid and decomposed. The decomposition has been referred to throughout as saussuritisation as epidote, lawsonite, zeolites, calcite, a secondary plagioclase, and micaceous products have been recognised. It is the same type of alteration as appears on a large scale among the xenoliths which are to be described later. In some cases a clear transparent felspar dominates, and in others the decomposed felspar, but both often appear together. The discrimination of the plagioclase is not simple, because lamellar twinning is not well developed. The lamellæ are often confused and intermittent, and many sections are not twinned at all. Such untwinned sections can be proved by their refractive index not to be orthoclase. Labradorite, with broad lamellæ and large extinction angle, has been detected. This labradorite is at times partly saussuritised. A second sodic plagioclase has been found with a smaller extinction angle, fine lamellæ, and lower refractive index. This second plagioclase is sometimes andesine and sometimes nearer oligoclase. It is a product of recrystallisation in which saussuritisation is but a stage, and the composition varies with the conditions of recrystallisation.

Quartz is a minor constituent and detected in several cases. It is abundant in examples where an ingress can be suspected.

Epidote appears throughout the series, but is more important in the mica schists and mica amphibolites. Generally, its percentage varies with the percentage of mica. It is found in characteristic honey-yellow or yellow-green grains frequently with crystal outlines. It may also be found in aggregates of little grains which may appear like small heaps. It may be intergrown with biotite or hornblende, and it may appear as poikiloblastic grains in chlorites, biotite, or hornblende. It may rarely be intergrown in parallel with zoisite (or clinozoisite). Even when the percentage of epidote is very small we may still find large grains enclosed in biotite or chlorite. The epidote crystals are occasionally found with nuclei of calcite and allanite.

Sphene is an abundant accessory mineral in most members of the series. It is frequently idioblastic and normally contains a crystal of magnetite as a nucleus. Specimen No. 5, where sphene does not possess this nucleus, is exceptional. The magnetite development varies from small crystals to large individuals, comparable in size with the hornblende, which are only coated with a thin rim of sphene. In the latter case the iron ore may total 6 per cent. Magnetite may also appear without the sphene. The occurrence is similar to the "titanomorphitokranz" of the German petrographers*, where sphene has recrystallised from decomposed ilmenite in amphibolites. The magnetite has been described as such because of the highly magnetic and polarised character of some separated grains, and because no violet colour was obtained when an HCl solution was reduced with tin†. In some sections a little red-brown rutile is associated with the magnetite. Pyrite is occasional and sporadic.

Colourless apatite becomes an important accessory in some cases. Its host is usually, though not necessarily, the felspar. The crystals may be minute, but in its best development we may get crystals comparable with the grain size of the rock.

Lawsonite is an interesting constituent. Being a saussuritisation product it obtains its best development in rocks with abundant saussuritised felspar, though it may also form from hornblende. It is partly intergrown with biotite, and the lobated character of the laminæ is characteristic. It is partly in grains and partly in thin microscopical veins. Occasionally the vein walls are lined with epidote while lawsonite forms the main vein filling. In such cases the epidote has crystallised before the lawsonite. Both the refractive index and the birefringence of the epidote are noticeably greater than those of lawsonite in such instances. Calcite may form vein filling with the lawsonite, and then lawsonite is found along the wall while calcite forms the centre. Calcite also occasionally appears in coarse granular crystals. Fluorite appears in grains, or is intergrown with biotite in the same manner as chlorite or lawsonite, while stilbite is well developed in one example. Stilbite, fluorite, lawsonite, and epidote may be found along joint planes and microscopic veins.

The rock types may be summarised thus—

No. 153.	Epidote biotite schist.
No. 5.	Amphibolite.
No. 412.	Biotite amphibolite schist.
No. 720.	Lawsonite mica amphibolite schist.
No. 630.	Quartz biotite amphibolite.
No. 629.	Amphibolite.
No. 631.	Amphibolite.
No. 637.	Amphibolite.
No. 634.	Amphibolite schist.
No. 634A.	Lawsonite amphibolite schist.
No. 635.	Lawsonite amphibolite schist.

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[*] Op. cit., vol. 1, p. 74.

[†] Since writing the above, some samples of iron ore from Cape Denison have been analysed by J. C. H. Mengaye, of the New South Wales Mines Department. It has been found that the magnetic properties do not vary proportionately with the titanium content. The more magnetic samples may have the higher TiO_2 value.

4.—CRYSTALLOBLASTIC ORDER.

The crystalloblastic order, as defined by Grubenmann*, is determined by the form development of the crystal grains. A mineral placed in the crystalloblastic order will assert its crystal form against all minerals that follow it in the sequence. The order is based on a fundamentally different conception to that on which the order of crystallisation of minerals in igneous rocks is based. In igneous rocks a definite order is obtained based on the principles of solubility and mass action which prevail in a rock magma. When, however, a set of conditions prevail which will stamp the special metamorphic characters on a rock mass, the whole alteration takes place while the rock remains solid. The new minerals resulting from the new set of conditions will arise at practically the same time. They will grow together, and any one mineral may be included in, or surrounded by, any other mineral. In doing so some minerals will exert their crystalline form against the adjacent grains of other minerals. For example, we may find felspar included in epidote, and we may also find epidote included in felspar. The felspar included in epidote will be rounded in outline while the epidote included in felspar will very likely possess crystalline boundaries. Epidote, therefore, stands above felspar in the crystalloblastic order†.

The crystalloblastic order is of value because the minerals possessing crystalline form in schists are those which possess the greatest crystallisation force. The speed of crystallisation may also be a factor in assisting or hindering crystalline form.

Grubenmann's teaching in this manner is not accepted by Leith and Mead‡. These authors are inclined to imagine that crystal habit or crystal dimensions influence the development of the new minerals, and believe that the mineral constituents are not of equal rank and do show a definite order of crystallisation. It is to be pointed out that Leith and Mead make no attempt to discriminate between sets of physico-chemical conditions grouped together in Van Hise's zone of anamorphism, and, therefore, do not recognise that a metamorphic rock may carry the impress of two or more sets of conditions. They have not appreciated the fact that Grubenmann has attempted to form a crystalloblastic order for each defined set of conditions, *i.e.*, for each zone. The crystal habits of the new minerals are but a reflection of these superimposed conditions, and the size of crystals in metamorphic rocks is a variable factor without important genetic connection. They have not shown that their order of crystallisation means anything more than an order of application of successive sets of metamorphic conditions.

The crystalloblastic sequence, as far as it can be observed in this suite of rocks, is—magnetite, sphene, epidote, hornblende and lawsonite, biotite and chlorite, felspar and quartz.

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* Op. cit., vol. I., p. 73.

† The expression of this interpretation of Grubenmann's crystalloblastic order is necessary, because the term has been given other meaning by Lahee in his paper "Crystalloblastic Order and Minerals," in the Journal of Geology, vol. 22, pp. 500-515. Lahee (p. 514) has confused order of origin with the crystalloblastic order.

‡ "Metamorphic Geology," C. K. Leith & W. J. Mead, New York, 1915, p. 187.

The magnetite is placed above the sphene because the common magnetite nucleus of the sphene sometimes appears idioblastic. Large crystals of magnetite, when not enclosed in sphene, may be xenoblastic and penetrated by idioblastic epidote. Biotite flakes, with their usual ragged ends, may penetrate the ragged ends of hornblende prisms, but the idioblastic cross sections of hornblende exert their form against biotite. Lawsonite is placed above biotite because it exerts its lobate outline against biotite. Sometimes lawsonite shows crystalline boundary against hornblende and sometimes the reverse is seen. Biotite and chlorite are inseparable ; so also are quartz and felspar, as quartz is always a very minor quantity.

5.—Chemical Characters of the Cape Denison Amphibolites.

In order to determine the chemical characters of the series, examples of two extreme members were selected for analysis. Nos. 153 and 629 have been, therefore, analysed in the Victorian Geological Survey Laboratory by A. G. Hall, under the supervision of P. G. W. Bayly. No. 153 is an epidote biotite schist with biotite developed almost to the exclusion of hornblende. No. 629 is an amphibolite in which hornblende dominates very largely over the mica, and it was chosen for analysis because its outcrop contains the remarkable xenoliths. Actually, its hornblende content is a little higher and its mica content a little lower than in the most typical examples. Such variation finds its explanation in the metamorphic differentiation that has occurred in this band.

	No. 153.	No. 629.
SiO_2	52·73	48·74
Al_2O_3	13·99	13·64
Fe_2O_3	4·31	3·31
FeO	9·19	9·98
MgO	3·27	7·12
CaO	5·98	10·34
Na_2O	1·73	1·96
K_2O	2·98	0·83
H_2O+	1·72	1·95
H_2O-	0·10	0·11
CO_2	strong trace	trace
TiO_2	2·14	1·26
ZrO_2	nil	nil
P_2O_5	0·90	0·14
SO_3	nil	nil
Cl	0·08	0·04
S	0·04	0·06
Cr_2O_3	0·03	0·05
MnO	0·39	0·35
NiO, CoO	0·03	0·01
CoO	trace	trace

	No. 153.		No. 629.
BaO	0·05	..	nil
Li_2O	trace	..	trace
O=Cl	0·02	..	0·01
O=S	0·01	..	0·02
Total	99·63	..	99·86
Specific gravity	2·953	..	3·030

These two analyses bear important resemblances. The silica percentages are relatively low and bear approximately the same ratio to the alumina. The total iron is almost identical in the two cases. Both percentages of magnesia are lower than the percentages of lime, and, further, the ratio of the magnesia to the lime is the same in each case. The soda percentages are not far different, and the water content is similar. Both are rich in titanium, and, in general, the similarity is sufficiently strong to emphasise the field observation that the two samples are of common origin.

At the same time the differences are interesting and important when compared with the relative mineral compositions expressed in Table 1. The high mica percentage in No. 153 involves a higher silica percentage and a noticeably higher percentage of total alkalies with potash in greater amount. The high hornblende percentage in No. 629 involves the correspondingly lower silica, the much higher percentages of magnesia and lime, and the much lower alkali total. The amounts of felspar are approximately the same in each case, and hence the alkali percentage of No. 629 gives approximately the amount of alkali in the felspar, and the extra amount in No. 153 can be attributed to the mica. There is considerably greater quantity of iron ore in No. 153, and its amount of Fe_2O_3 is correspondingly greater. There is no corresponding variation with FeO, as varying quantities of FeO are required for the ferromagnesian constituent. The larger amount of sphene in No. 153 is also partly responsible for its higher titanium percentage, but the differing percentages of P_2O_5 are precisely reflected by the differing percentages of apatite. The chlorine is probably associated with the apatite, and thus appears in greater amount in No. 153. The sulphur is derived from the very occasional grains of pyrite. Cr_2O_3, MnO, NiO, and CoO are no doubt contained in the ferromagnesian. Finally, No. 153 is notable for its definite percentage of barium.

Since No. 153 expresses the composition of the bands with high mica content on the western side of Cape Denison and No. 629 gives the composition of the amphibolites on the east, the intervening bands, containing varying proportions of biotite and hornblende, can confidently be expected to possess a chemical composition within the limits of these two extremes. The actual variation could, indeed, be approximately estimated from the mineral content expressed in Table 1—*e.g.*, the greater the mica percentage the nearer will the silica percentage approach that of No. 153. The percentage of the minor constituents, like TiO_2 and P_2O_5, will vary in much the same manner as the corresponding accessory minerals.

Both analyses bear marked resemblances to analyses of basic igneous rocks. While this could be illustrated by comparison with numerous examples, it is well illustrated by assuming the rocks to be igneous and then treating them in accordance with the principles of the American Classification of Rocks. No. 153 is then a member of the division—Class II., Dosalane; Order 4, Austrare; Rang 3, Tonalase; Sub-Rang 3, Harzose. The examples of this division quoted by Washington* are chiefly afforded by granodiorites, diorites, andesites, and porphyrites. No. 629 falls into Class III., Salfemane; Order 5, Gallare; Rang 4, Auvergnase; Sub-Rang 3, Auvergnose. The examples quoted of this division include mainly diabases, gabbros, basalts, some porphyrites, and camptonites. Both rocks, judged, therefore, from their chemical composition, are likely to be metamorphosed basic igneous dykes. No. 153, being more siliceous, probably approached rather towards a porphyrite, while No. 629 would have probably tended to typical diabase or dolerite. The association with a metamorphosed granitic mass suggests their original character as basic lamprophyres; but the small percentage of the alkalies renders it unlikely. Metamorphosed lamprophyres or lamproschists are recorded from Garbh Allt, a mile S.E. of Glencaloie Lodge†, and in the analysis the alkali percentage is as high as 6·95. The corresponding percentages of these Cape Denison rocks are 4·71 and 2·79.

It is now necessary to examine these analyses with the view of classifying the rocks in Grubenmann's classification of the crystalline schists. Before doing so, however, we give a resumé of the method of classification as little or no use of it has hitherto been made in the English language. In the present state of our knowledge of the crystalline schists this classification has considerable value. It has been put forward to organise our knowledge, but a more complete understanding of the metamorphic processes and their products will cause, at least, modification.

Grubenmann's Classification of the Crystalline Schists.

Grubenmann has classified the crystalline schists primarily on a chemical basis. The chemical data yield him 12 groups, each of which is divided into three sub-groups which are based upon the typical features associated with the physico-chemical conditions of his three zones of metamorphism. He has pointed out that classification on any other basis, *e.g.*, mineral composition, mode of origin, original character, etc., will not succeed in bringing similar crystalline schists together, and, at the same time, maintain their marked individuality which distinguishes them from the igneous and sedimentary rocks. The variation, for example, of mineral content in this suite of rocks under consideration, which bear strong chemical analogies, are similar in origin, and have been subjected approximately to similar metamorphic conditions, is evident from Table I. Mineral content is, therefore, useless as a classificatory basis if the classification is to succeed in grouping together similar species. The following are the groups appearing in his classification :—

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* "Chemical Analyses of Igneous Rocks," H. S. Washington. Professional Paper, No. 14, U.S. Geol. Surv., 1903.

† "The Geology of Ben Wyvis, Carn Chuinneag, Inchbae, and the surrounding Country." Memoir Geol. Surv. Scot., No. 93, 1912, p. 125.

1. Alkali felspar gneisses.
2. Aluminium silicate gneisses.
3. Lime soda felspar gneisses.
4. Eclogite and amphibolites.
5. Magnesium silicate schists.
6. Jadeite rocks.
7. Chloromelanite rocks.
8. Quartzite rocks.
9. Lime silicate rocks.
10. Marmorites.
11. Iron oxide rocks.
12. Aluminium oxide rocks.

Each group has its kata, meso, or epi division based on the characteristics of the lowest zone, the middle zone, and the highest zone of metamorphism. Each division again consists of families whose number depends on the number of known types of schists contained in the division.

The classification is made quantitative by the use of an adaptation of Ozann's treatment of a chemical analysis. The analysis is first modified so that the TiO_2 and P_2O_5 are reduced to equivalent amounts of SiO_2 percentage ; the Fe_2O_3, MnO, Cr_2O_3, NiO, CoO, are reduced to, and then added to the FeO percentage, the BaO, SrO, to the CaO, and the water neglected. The values of the seven constituents are then reduced to their molecular proportions, which, in turn, are reduced to molecular percentages.* From the molecular percentages seven group values, designated S, A, C, F, M, T, K, are obtained in the following manner :—

S denotes the SiO_2 in molecular proportion.

A is the similar sum of K_2O and Na_2O which is combined with Al_2O_3 in the 1 : 1 proportion.

C is the CaO combined with Al_2O_3 in the 1 : 1 proportion.

F is the sum of FeO and MgO and that part of CaO which is not absorbed in the 1 : 1 proportion with Al_2O_3.

M is the residual CaO used in F.

T is the residual Al_2O_3 not absorbed in the 1 : 1 proportion with K_2O, Na_2O, and CaO.

K is the value of the quotient $\frac{S}{6A + 2C + F}$

The values S, K, A, C, F are used exactly with Ozann's meaning ; K, however, is only important here in determining the degree of acidity of the crystalline schist. M gives the absolute amount of CaO in F and is useful in dealing with lime silicate rocks signifying their sedimentary origin. T is necessary to express the high Al_2O_3 content in some gneisses, especially those derived from clay sediments. No term is introduced to express the relation of the alkalies to one another as it is undesirable in the present state of our knowledge of the crystalline schists. A classification at present can only deal with the broader features.

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[*] The extra step, explained by Grubenmann, op. cit., vol. II., p. 12, of reducing the seven values to percentage values before determining the molecular proportions, is superfluous.

The group values together, not individually, represent the chemical characteristics of each main group of the classification. For each main group there is a set of mean group values with a definite range of variation.

The group values for any example are represented graphically by points in Ozann's triangular projection. If the factor 20 is used, each side of the equilateral triangle is divided into 20 and lines parallel to the sides are drawn through each division. Perpendiculars are drawn from the angular points on to the sides and the projection values a, c, f, are measured from the base along the perpendiculars. The projection values are calculated thus—

$$a = \frac{20A}{A + C + F}, \quad c = \frac{20C}{A + C + F}, \quad f = \frac{20F}{A + C + F}$$

The result of this is that differing groups of schists occupy more or less distinct areas in the triangle, and the position of a schist on the projection may give a means of indicating the origin, igneous or sedimentary.

The Classificatory Position of the Cape Denison Amphibolites.

If the analyses of rocks Nos. 153 and 629 be treated in this manner, we obtain the following results :—

	No. 153.			No. 629.		
	Reduced Analysis.	Molecular Proportion.	Molecular Percentage.	Reduced Analysis.	Molecular Proportion.	Molecular Percentage.
SiO_2	55·09	918	61·6	49·80	830	53·4
Al_2O_3	13·99	137	9·2	13·64	133	8·6
FeO	13·49	188	12·6	13·36	186	12·0
CaO	6·00	107	7·2	10·34	185	11·9
MgO	3·27	82	5·5	7·12	178	11·5
K_2O	2·98	32	2·1	0·83	9	0·6
Na_2O	1·73	27	1·8	1·96	32	2·0
	96·55	1,491	100·0	97·05	1,555	100·0

Group Values.

	S.	A.	C.	F.	M.	T.	K.
No. 153	61·6	3·9	5·3	20·0	1·9	0	1·14
No. 629	53·4	2·6	6·0	29·4	5·9	0	·94

Projection Values after Ozann.

	No. 153.		No. 629.
$a = \dfrac{20A}{A + C + F}$	2·7	....	1·4
$c = \dfrac{20C}{A + C + F}$	3·6	....	3·1
$f = \dfrac{20F}{A + C + F}$	13·7	....	15·5

Examination of these group values enables one to place both rocks among the eclogites and amphibolites of Group IV. No. 629 is a typical amphibolite not far removed from the mean group value. No. 153 approaches the plagioclase gneisses of Group III., and the group values S and M actually fall within the variation limits of this group; but, nevertheless, its position on the projection is much closer to the mean position of Group IV. than to the mean position of Group III. Since both examples fall into Group IV., we are able to assert that the whole suite of rocks considered falls into the same group.

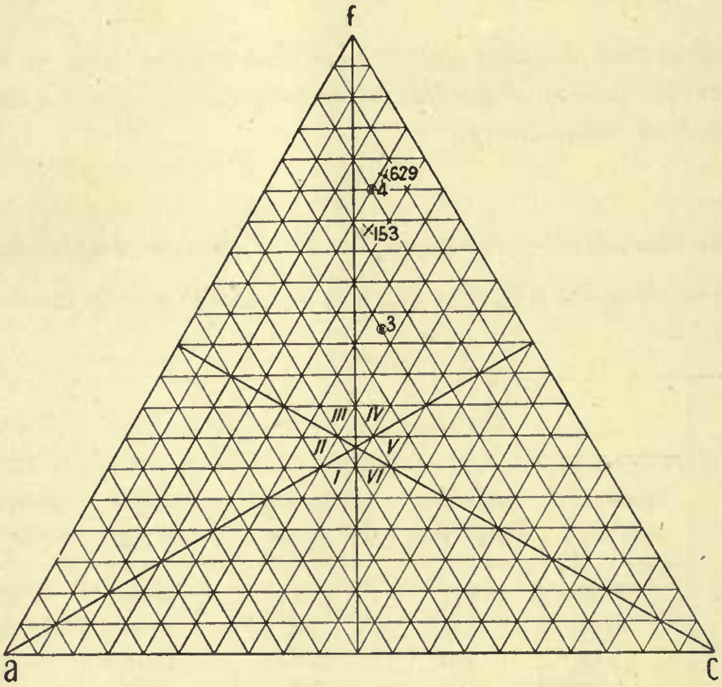

Fig. 4.

3. Mean Value of Group III., the Plagioclase Gneisses.
4. Mean Value of Group IV., the Eclogites and Amphibolites.
153. Epidote Biotite Schist, Cape Denison.
629. Amphibolite, Cape Denison.

In order to determine the subdivision of Group IV. it is necessary to recall the microscopical characters. When we do so we find that the rocks do not wholly present the characteristics of either the epi division or the meso division. In cases where the clear felspar is albitic and other plagioclase is much saussuritised, where biotite is replaced by chlorite, where epidote partly replaces the calcic plagioclase thereby absorbing a good deal of the lime content, where calcite also absorbs some of the lime content as in No. 412, and where lawsonite is present, we have features of the epi division. Where, however, we find considerable quantity of recrystallised clear andesine, biotite without chlorite, and abundant clear hornblende with only rare transition to epidote, to chlorite, or to glaucophane, we have dominant meso division features. Yet it is to be noted that abundant saussurite and lawsonite is found with clear hornblende, saussurite with clear felspar which is not albite, chlorite and epidote with biotite in the same section. It, therefore, appears that the series has to be considered as more representative of the transition types between the meso and epi divisions.

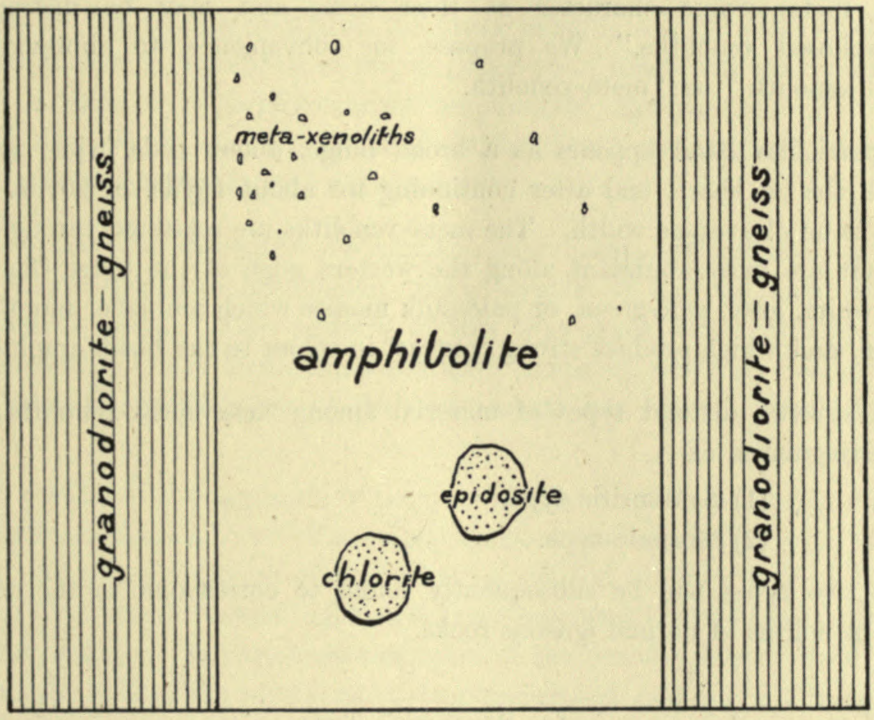

Fig. 5.

Diagrammatic Sketch of the Amphibolite Dyke No. 629 with the Scattered Meta-xenoliths and the Clots of Chlorite Rock and Epidosite.

No. 153 is an epidote biotite schist and has suffered higher recrystallisation than the epidote chlorite schist in family A of the epi division. With the temperature and the uniform pressure approaching that of the middle zone, the chlorite has passed over to biotite. The actual transition is found in No. 630, where the chlorite passes first into green biotite and the latter into brown biotite. That the epidote remains after the chlorite has changed to biotite is due to the fact that epidote can retain its water at a much higher temperature than chlorite. Grubenmann points out that such individual characteristics of mineral and rocks necessarily cause the features of one zone to encroach in varying degrees on an adjacent.[*] The abundance of biotite in any of these specimens probably means, therefore, a previous abundance of chlorite. This abundance of chlorite, in turn, means abundant chloritisation of the pyroxenes of the primary diabase, which may have occurred either in normal weathering or in the upper parts of the epizone. As, however, hornblende as well as biotite could develop from chloritised pyroxene, the amount of biotite cannot be considered an index of the amount of primary chloritisation.

6.—METAMORPHOSED XENOLITHS (META-XENOLITHS).

One band of amphibolite (No. 629), outcropping near the centre of the Cape Denison area, is phenomenal in containing a large number of xenoliths.[†] These xenoliths possess the same metamorphic character as their host, and may be distinguished as "metamorphosed xenoliths." We propose, for convenience, to abbreviate "metamorphosed xenolith" to "meta-xenolith."

The particular band appears as a broad bulge, about 4yds. wide, issuing from underneath the ice sheet, and after continuing for about 15yds. or 20yds. it narrows down to a band of average width. The meta-xenoliths are scattered through the whole outcrop, but are most abundant along the western edge of the bulge (fig. 5). They consist of white, grey, pale-green, or pale-pink masses which are never more than a few inches long, and which produce strong contrast in colour to the black amphibolite host.

There are two distinct types of material among these meta-xenoliths, and they may be distinguished as—

(1) Saussuritic type.
(2) Gneissic type.

These two types will be subsequently found to correspond to the cognate and accidental xenoliths of normal igneous rocks.

1.—*Saussuritic Type.*

The saussuritic type includes the pale-green and pale-pink masses, which may be again subdivided into—

(*a*) Those composed wholly of saussurite—the individual type.
(*b*) Those composed of an aggregate of saussurite and hornblende—the composite type.

(*a*) The Individual Type of Meta-xenolith.—The meta-xenoliths composed wholly of saussurite[‡] may retain the original outline of a primary felspar crystal. The largest example in the collection of such a crystal is 1in. broad, and shows the re-entrant angle of a simple twin (Plate X., fig. 6). In other cases the saussurite masses are both rounded and angular. The largest rounded mass among the specimens in the collection is 2in. in diameter. A remarkable example of an angular mass of saussurite is shown on Plate X., fig. 5. Here the section is a perfect triangle, with the sides measuring 2½in., 1⅝in., and 1⅝in. The boundary is macroscopically sharp, except for a minor length which is a little ragged at the left hand corner and which is scarcely noticeable in the photograph. A small amount of hornblende and epidote is macroscopically visible in this example. In all cases the junction between the saussurite and the amphibolite is normally sharp, irrespective of the crystalline, angular, or rounded nature of the contour. Some examples, which are illustrated on Plate IX., fig. 4, consist of amphibolite uniformly and thickly studded with small patches of saussurite averaging ¼in. in diameter. A boulder found on the lower moraine a little north of the outcrop is used as the diagram, but similar examples collected *in situ* are in the collection. The appearance is that of a porphyroblastic amphibolite, though there is considerable variation in size. Such would be a likely explanation were they not only found in association with the better defined meta-xenoliths.

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[*] Op. cit., vol. I., pp. 70, 71.

[†] We use the term "Xenolith" in the same sense that it is applied to igneous rocks. Gruhenmann does not provide a special equivalent in his system of nomenclature for the crystalline schists.

[‡] The term "Saussurite" is used in the same sense as given by Weinshenck (Petrographic Methods, trans. Clarke, p. 336) and by Flett ("Geology of the Lizard and Meneage," Mem. Brit. Geol. Surv., 1912).

Macroscopically the saussurite is a compact, stony mass, in which one can sometimes distinguish black specks of hornblende, green crystals of epidote, and, more rarely, white patches of calcite. Thin sections of this type reveal the crystalline aggregate known as saussurite. The larger xenoliths have produced relatively coarse crystalline aggregates wherein identification of the constituents has become possible (Plate II., fig. 4).

A good portion of the aggregate is always a cloudy, brightly polarising mass similar to the saussuritised felspar, to which reference has been made in dealing with the previous rock types. At times a system of parallel lines, defined by thin lines of hematite or limonite, are observed in parallel light, and these represent traces of the broad lamellæ of the primary felspar. In rare instances relics of the primary felspar itself are found. In such cases the bulk of the crystal has been saussuritised, and only a few clear lamellæ are left. A section was found normal to these primary lamellæ and gave an extinction angle of 44°, measured from the lamellæ bands. The primary felspar is highly calcic and near the anorthite end of the series.

In the confused aggregate epidote is prominent, and the large grains can be recognised at once by the brilliant polarisation colours. It is a very pale epidote with feeble pleochroism in the thin section and with the (001) and the (100) cleavages well developed. The optic axial plane is normal to the cleavages as usual, and from the (001) cleavage the extinction angle is approximately 25°, and from the (100) it is approximately straight. The outline of the large pieces is usually granular, but sections showing two cleavages with crystal boundaries may be found. Sometimes the larger grains are bordered with finely granular masses of a rather darker epidote. The latter is much more abundant in some sections than in others, and it seems to mark a stage in the decrystallisation of the felspar. Associated with the epidote is clinozoisite and zoisite, which are often intergrown in the one crystal. Clinozoisite is the more abundant, and is readily detected by the ultra blue polarisation colour. Like the epidote, two cleavages are present, and it is found to have approximately straight extinction with reference to one cleavage and a large extinction with reference to the other. In several instances the optic axial plane was determined to be perpendicular to the cleavage, and the small curvature of the bar in the interference figure in sections normal to an optic axis indicates a large optic axial angle. Clinozoisite may also be bordered by finely granular material. The zoisite, with its bluish-grey polarisation colour, is distinct from the clinozoisite and the epidote. Wherever determined the optic axial plane is normal to the cleavage indicating the variety zoisite β.

Lawsonite has been found in some sections in large individuals and in small veins. In the development of some of the crystals a brown micaceous mineral, like poorly-developed biotite, has been thrown out along the cleavage planes. This fact may be interpreted as evidence of the contemporaneous development of the intergrown lawsonite and biotite reported in the lawsonite amphibolites.

Green pleochroic chlorite is present, and may show the usual anomalous polarisation colour or a pale-greenish-white colour between crossed nicols. The amount of chlorite is very small in some cases and in others the aggregates may be radial. A white mica is present, which is probably muscovite. When best developed it is clear and colourless, with cleavage and the usual absorption. Sometimes it presents a confused and ragged appearance with the laths set in a criss-cross manner.

In similar association to the white mica is scapolite, with its low refractive index and brilliant polarisation colours. It has been identified by its uniaxial and negative character. How much of the brightly polarising mass is scapolite and how much is white mica must remain an unsettled question. Calcite is sometimes found in plates of irregular outline, and a small segregation of calcite is present in one instance. Grains of pyrite and magnetite are nearly always present, and in several cases the pyrite is visible macroscopically.

In this mineral aggregate there is sometimes a clear felspar which is either untwinned or finely lamellar twinned. The refractive index is moderately low, but always above Canada balsam. In No. 628 (5) the extinction angle goes up to 18° when measured in sections with cleavage but without twinning. It is therefore interpreted as either oligoclase or andesine. In this instance the felspar of the adjoining amphibolite is quite clear and recrystallised, and seems to be identical with the clear felspar in the saussurite. The latter is sometimes fringed with the clear felspar which then comes in contact with the clear felspar of the amphibolite. An extinction angle of 17° can be measured among the grains in the amphibolite. Hence, if both are identical the determination must be andesine.

This mineral aggregate, even apart from the primary felspar, is conclusive that we are dealing with the decomposition products of a highly calcic felspar. The crystalline outline, as far as it is observable, agrees with a felspar. The secondary felspar in saussurite is usually recorded as albite, but the composition of the felspar depends on the conditions under which saussuritisation takes place. The conditions under which muscovite, scapolite, zoisite, and clinozoisite form are not those under which secondary albite can form. Among the minerals identified above, lawsonite and chlorite are unimportant or absent in the best or coarsest crystalline aggregates.

(*b*) The Composite Type of Meta-xenolith.—The composite type of meta-xenolith is formed of a number of saussurite " crystals " set in a hornblende matrix. These aggregates may have an irregular, rounded, or angular outline which frequently appears macroscopically sharp, but it is not necessarily so. A diagrammatic example of one of these aggregates is given on Plate IX., fig. 3. In this case the boundary is sharp and some of the saussurite masses have preserved the shape of the primary felspar crystals. The coarse grained character of the primary xenolith is here quite evident. A remarkable angular example is illustrated on Plate IX., fig. 2. These two " diagrams " were collected from the lower moraines, which consist almost entirely of local rock, at a point a few yards north of the occurrence *in situ*. A rectangular example obtained *in situ* is shown on Plate IX., fig. 1. In all these cases the apparently sharp boundary is actually a line of interlocking saussurite and amphibolite, and the saussurite aggregates throughout the block are set in a mass of interlocking, granular hornblende. In type the saussurite is similar to that described in the individual type of meta-xenolith, but here in the smaller crystals recrystallisation has not been so intense. Further, in the specimens that have been examined, lawsonite and chlorite and calcite are more abundant than in previous cases. In addition, sphene is sometimes found in these aggregates. The hornblende is precisely similar to the hornblende in the amphibolites, and the clusters of granular hornblende may readily represent the decrystallisation products of a large primary augite.

There is every reason to believe that these composite meta-xenoliths represent the relics of clots of coarse-grained rock of the same composition as the primary dolerite. No minerals, except those which have become recognisable in the saussuritic aggregates, are found in the clots that are not found in the amphibolite proper. The clots consisted chiefly of coarse felspar and coarse augite. The coarse felspar is now a saussurite complex and the coarse augite is now an aggregate of granular hornblende.

2.—*Gneissic Type of Meta-xenolith.*

The gneissic type of meta-xenolith shows considerable variation in colour, shape, and size in the hand specimen. They are indiscriminately mixed with the saussuritic meta-xenoliths. Some examples possess a grey colour and so bear strong resemblance in the hand specimen to the grey granodiorite that surrounds the amphibolite. Other examples have a pure white colour, and others, again, have a vitreous grey colour which is suggestive of a colour change during recrystallisation.

The shape, in many instances, is clearly angular and fragmental, and the corners may be well preserved. Frequently the gneissic fragment is drawn out into a lenticular shape in the direction of the schistosity (Plate X., fig. 1). In this example the lenticular bodies are not symmetrical to the schistose plane. A side view of the same specimen is shown (Plate X., fig. 2). Here a meta-xenolith at the upper right hand corner is almost triangular in outline, yet the schistosity of the rock can be distinctly seen to follow through the inclusion from the amphibolite irrespective of its shape. Hence the amphibolite and the fragment must have formed a single unit before the reception of the metamorphic impress. In fewer cases the cross section is elliptical and, therefore, symmetrical to the schistosity; in such examples recrystallisation and rearrangement are evident. The back and front views of another specimen are illustrated on Plate X., figs. 3 and 4, where the gneissic meta-xenoliths are not lenticular but possess an angular and variable shape.

The outline of the gneissic inclusion is often clear and sharp, though we may find it slightly embayed. There are instances, however, where the entire boundary is lost and replaced by a transition between the amphibolite and the white gneiss. An inclusion is also observed where part of the boundary is sharp and part indistinct. This indefinite boundary might be accounted for by postulating chemical action between the xenolith and the host before the metamorphism. Such, however, is not a necessary hypothesis, because evidence will be produced later which leads us to discount the normal face value of transitions in metamorphic rocks, and to believe that such transitions can arise during the progress of the metamorphism. That there has been an adjustment of molecular equilibrium along the junction during metamorphism seems evidenced by the lines of amphibolite which may be sometimes seen threading their way from the host in the direction of the schistosity of the inclusion. Though the junctions may be sharp there is perfect crystalline continuity and an interlocking of crystals across them.

In thin section (No. 628·3) the fragments are found to be clear granoblastic aggregates of quartz and felspar (Plate II., figs. 1 and 2). The grains have a tendency to be rounded or elliptical, and are of moderately even size, averaging about ·16mm. in diameter. Actually each grain has irregular outline, is much embayed, and always interlocks with its neighbour. Undulose extinction is marked in the quartz and sometimes in the felspar. The felspar often possesses lamellar twinning, and as its refractive index is near that of quartz, and sometimes above, it is identified as andesine. Small crystals of biotite and chlorite are distributed through the mass and show a tendency to parallel arrangement. Hornblende is present in rather larger crystals, and epidote, clinozosite, and other saussuritic products are scattered in groups with a tendency to linear distribution. Magnetite and pyrite are accessories.

In other cases (No. 628·6) porphyroblasts of quartz and felspar are found. They possess the lenticular cross section, and are relics of the primary minerals. The quartz porphyroblasts have just commenced to develop a broken granular appearance and show the intermediate stages in the destruction of a large primary crystal. One quartz porphyroblast is a fractured granulitic aggregate, though it still retains its entity in both ordinary and polarised light. In another case fracturing has not occurred, and the central portion of a porphyroblast still shows unbroken strings of linear inclusions, though incipient granulitisation appears between crossed nicols. These strings run diagonally across the plane of schistosity. The section is elliptical and the ends of the longer diameter consist of a granular interlocking quartz aggregate in which each grain possesses different optical orientation. It is an excellent example of the result of solution at the points of maximum pressure with simultaneous deposition at the points of minimum pressure in the plane at right angles to the direction of pressure. In the fractured quartz porphyroblast secondary minerals like chlorite, epidote, and calcite now appear along the fractures. The felspar porphyroblasts are also elliptical. Their calcic nature is evident by the saussuritic products in which chlorite and epidote are definitely recognisable. The centre of one porphyroblast is a granular aggregate, produced by the breaking down of the primary felspar, which consists chiefly of clear secondary felspar with lower refractive index with some epidote, chlorite, and calcite. The remainder of the felspar porphyroblast, apart from the granular nucleus, has also suffered decrystallisation and now presents a "peg" structure. Small rounded blebs of secondary felspar appear in contrast to the primary felspar in polarised light.

These porphyroblasts of quartz and felspar are set in a much finer granoblastic aggregate of quartz, clear felspar, and saussuritised felspar with sporadic grains of magnetite and pyrite, epidote, chlorite, hornblende, and sphene. The typical grain is here elongated in the direction of the schistosity, giving evidence of a certain amount of crystallisation schistosity. Idioblastic crystals of apatite are included in the quartz. Besides the granular individuals of saussurite in this section there are lenticles of saussurite from a neighbouring saussuritic meta-xenolith. The cloudy appearance has occasionally disappeared and there is left a mass of epidote and chlorite. Some of the layers, rich in saussurite, can be traced directly into the enclosing amphibolite, and some contain sphene and hornblende.

The gneissic meta-xenoliths, therefore, possess characters which are essentially foreign to the amphibolite host. They possess affinities to the surrounding gneiss though they seem to show a slightly greater degree of recrystallisation.

Origin of the Meta-xenoliths.

1. *Saussuritic Type.*—The individual variety of saussurite inclusions have been derived from the decomposition of a felspar. The primary felspars, particularly those with crystal outline, may have been phenocrysts of intra-telluric origin brought up with the injection of the dyke magma. But the presence of the angular and rounded masses

of saussurite show that we are not dealing with a porphyritic dyke rock, while the irregular and local distribution is strong evidence of cognate xenoliths. No one can suppose that the meta-xenolith in Plate X., fig. 5, could be anything but a fragment of a pre-existing felspar crystal. Large calcic felspars do develop in amphibolites under the metamorphic conditions of the kata zone or the lower meso zone. An example of this nature (No. 212) was found among the boulders on the moraine and the porphyroblasts (Plate IX., fig. 5) do not bear a trace of decomposition in thin section. Such crystals would become saussuritised if subjected for a sufficient length of time to the conditions of the epi zone. We have found no evidence to suggest that any of the amphibolites found *in situ* on Cape Denison have been subjected to the kata zone conditions, and no such hypothesis would explain the extraordinary local, irregular, and unsymmetrical distribution.

The composite variety of saussuritic meta-xenolith is also best explained as a metamorphosed cognate xenolith. It is not likely that they are unabsorbed residuals of primary rock which has survived the metamorphism. Their boundary is too definite and they actually bear the same metamorphic impress as the amphibolite itself. They are fragments of a rock of the same composition as the amphibolite, but of much coarser grain than the primary dolerite. They have been cognate xenoliths brought up from the magma reservoir, and probably represent differentiation products produced by crystallisation in that reservoir.

2. *The Gneissic Type.*—It has been shown that this type of inclusion is foreign to the enclosing amphibolite, but that it is related to the granodiorite gneiss which surrounds the amphibolite. Their unsymmetrical character and arrangement can be accepted as definite evidence that they attained their present situation before the reception of metamorphic characters. There is no alternative but to consider them as "accidental xenoliths" or fragments which have no genetic relation to the enclosing amphibolite, and which have been caught up during the injection of the primary dolerite dyke. Xenoliths have been frequently reported in the basaltic and doleritic dykes, and such was the original nature of this amphibolite host.

Significance of the Meta-xenoliths.

The consideration of these different kinds of meta-xenoliths collected from the same small area shows conclusively that their host is an igneous rock intrusive into the surrounding granodiorite. There can be no question of bedded tuff.

The marked angularity of some of the fragments means that the xenoliths did not travel far along the dyke channel. The saussuritic type must have come from the magma reservoir, and therefore the present surface must be close to the original magma reservoir. The gneissic xenoliths may have been fractured from the walls of the dyke channel and not necessarily from the roof of the magma reservoir.

Analogous Occurrences.

Xenoliths have been frequently reported in normal dyke rocks, and a summary of a number of such occurrences in Europe and America has been recently made by Powers*. Xenoliths in dykes which are now represented by metamorphic rocks, are much less frequent. Flett† has recorded examples from the Lizard district where dykes of gabbro schist and gabbro pegmatite contain inclusions of serpentine, and where epidiorite dykes contain inclusions of red granite.

I am not aware of the recognition of xenoliths within amphibolite dykes. In Beinn Lair and Meall Mheinnidh, of the Loch Maree and Gairloch District, C. T. Clough‡ has reported certain zones of hornblende schist which contain lenticles of a dirty white opaque susbstance which Teall identified as saussurite. A considerable number of these lenticles are more than 1ft. long, while some exceed 3ft. Their long axes lie parallel with each other in some patches, while in others they do not. The long axes are independent of the foliation of the schist. The lenticles have an irregular distribution, and an isolated instance is recorded at a distance of 60yds. from any others. Clough, finding difficulty of explanation, decided that they more probably represent concretions in an igneous rock before its conversion into schist, and that they may have been originally nearly spherical and analogous to spherulites.

It is quite likely that this occurrence in Scotland is analogous to the occurrence of saussuritic meta-xenoliths at Cape Denison. There is no marked angularity of the fragments in the Scottish instance, neither is there more than one type of fragment recorded, nor is the dyke-like nature of the host obvious. Nevertheless it is quite possible that the Scottish saussurites were cognate xenoliths brought to their present position by an invading magma before the development of metamorphic action. From quite independent sources Clough considers§ that there is little doubt that the hornblende schists were intrusive rocks.

7.—THE ORIGIN OF THE AMPHIBOLITE SERIES.

We have now presented the field, microscopical, and chemical characters of the amphibolite series, and we may now summarise the evidence bearing upon its origin.

Field Evidence.—In the first instance field observations strongly suggested that this suite of rocks constituted a parallel system of intrusive dykes. The uniform width, the frequent sharp line junction, the linear trend, and their persistency are valuable criteria. Fresh from the study of a parallel system of dykes|| the likeness to such was found to be highly suggestive. Bulges or swellings in the dyke channels had been

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* "The Origin of Inclusions in Dykes," S. Powers, Journ. Geol., vol. 3, p. 1.

† "The Geology of the Lizard and Meneage," J. S. Flett & J. B. Hill, Mem. Geol. Surv. Gt. Britain, Sheet 359, 1912, pp. 94-128.

‡ "The Geological Structure of the North-West Highlands of Scotland," Mem. Geol. Surv. Gt. Britain, 1907, p. 243.

§ Op. cit., p. 240.

|| "Preliminary Notes on the Monchiquite Dykes of the Bendigo Gold Field," Proc. Roy. Soc. Vict., 1911, p. 1.

seen in the Bendigo mines, and a broken surface outcrop in a metamorphic series is not unfavorable when such can appear in the unaltered series at Bendigo. The detached fragments of the dykes which are encircled by gneiss, and which could be mistaken for inclusions caught up by the invading magma, are undoubtedly related to and belong to the dyke magma.

Xenolith Evidence.—The discovery of metamorphosed xenoliths in one outcropping band of amphibolite is very important evidence of igneous and intrusive origin. The fragments of gneiss with sharp boundaries and with marked likeness to the surrounding gneiss possess a composition fundamentally different from that of the amphibolite host. The saussuritic type of meta-xenolith is one that might be expected to come from the magma reservoir from which the dykes issued. Knowing the granitic nature of the surrounding gneiss, it is impossible to conceive these xenoliths as undigested fragments of an igneous or of any other pre-existing rock.

Structural Evidence.—No relic of any kind of sedimentary structure is to be found. The typical granoblastic structure is in this case more suggestive of igneous origin.

Mineralogical Evidence.—It would be difficult to account for the suite of minerals, particularly the abundant saussuritised felspar, the relic felspar, and some well-formed apatite crystals, on any other hypothesis than that of igneous origin. The uniform variation in mineralogical composition of the different members of the series, which is illustrated in Table I., and which reflects uniform variation in chemical composition, indicates an igneous differentiated rock series.

Chemical Evidence.—The chemical analyses bring forward strong evidence of derivation from doleritic rocks. The analyses are similar in all essential points with analyses of diabases or dolerites. The definite grouping, on quantitative data, among the amphibolite group of the crystalline schists, is further evidence when we recall that many members of this group have arisen from diabasic dykes*.

The total evidence is thus conclusive that this suite of rocks from Cape Denison, conformable to the general foliation of the country, is the metamorphosed equivalent of a system of parallel igneous dykes. The dykes have intruded the granite prior to the development of the foliation. The granodiorite and dykes have then suffered the same metamorphic conditions with varying amounts of recrystallisation. The surrounding granodiorite excludes any possibility of the amphibolites representing altered bedded tuffs.

The nature of the primary dyke corresponds with a diabase or a dolerite whose mineral composition has been calcic felspar (labradorite), pyroxene, biotite, ilmenite, and apatite. No trace of serpentine is found, and, as serpentine can be preserved under epi zone conditions, it is concluded that no olivine was present in the primary.

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* "Die Kristallinen Schiefer," vol. II., p. 94. "Data of Geochemistry," F. W. Clarke, Bull. 330, U.S.A. Geol. Surv., p. 508.

The calcic felspar has been saussuritised, rarely persisting as a relic. The saussuritisation here is not a simple weathering process. Normal surface weathering is absent in Adelie Land, and the mineral products in saussurite are perfectly fresh, even after exposure at the surface. Members of the epidote family, chlorite, lawsonite, occasional zeolites, a secondary white mica, scapolite, and a secondary sodic felspar, have been recognised in the saussurite. Part of the saussuritised felspar has recrystallised, and in some cases we get clear andesine formed. The pyroxene has been completely changed. It is replaced by clear hornblende in the amphibolites, by biotite and epidote in the biotite epidote schists, and by both hornblende and biotite with associated epidote in the biotite amphibolites. In discussing the zonal changes, it has been considered that the biotite has developed through a chloritic stage, and that the chlorite was derived directly from the pyroxene. It is probable, however, that there was a little primary biotite in the diabase. The amount of mica in the amphibolites is approximately constant, and therefore cannot be dependent on a varying amount of chloritisation of the pyroxene. Further, the chlorite in these members appears regularly in large broken plates, which are sparsely distributed, and which are always penetrated poikiloblastically by epidote, together with clear quartz or felspar and iron ore. Such chlorite can be considered as produced in the decrystallisation of primary biotite*. The primary ilmenite has been altered to leucoxene, which has recrystallised as sphene, or it has decomposed into sphene and magnetite according to the equation given by Van Hise†. It is doubtful whether all the titanium is dissociated from the iron though the occasional presence of rutile rather suggests so. Certainly the larger grains are little magnets. The apatite has remained unchanged.

Either during or subsequent to the metamorphism fracturing occurred and the fractures have been filled with quartz, felspar, epidote, lawsonite, and calcite. Such epidote and lawsonite, etc., may be subsequent to the epidote and lawsonite in the schists, but cannot be used as an argument to show that all the epidote and lawsonite is formed subsequent to the schistosity. The epidote that takes definite part in the foliation must be considered as a primary metamorphic mineral of the same standing as biotite or hornblende. The epidote percentage has been shown to vary sympathetically with the biotite percentage which, in turn, varies inversely with the hornblende percentage. Further, the biotite or chlorite may be moulded on to perfect crystals of epidote in a manner which is impossible on a theory of subsequent epidotisation. The mineral-filled fractures do show that the rocks have been in a zone containing water. As fracturing may occur under the conditions of excessive stress in the epi zone of metamorphism, and as water may be present in this zone, there is no need to dissociate these minute fractures from the metamorphic characters.

In this manner, then, a diabase or dolerite containing calcic felspar, pyroxene, biotite, ilmenite, and apatite has been converted into an epidote biotite schist or an amphibolite containing saussuritised felspar, sodic felspar, hornblende, biotite, chlorite, epidote, magnetite, sphene, pyrite, apatite, and rarely rutile and fluorite. These changes have, at times, been accompanied by the addition or transfer of material, and, in some cases, it is very important and leads to a theory of metamorphic differentiation.

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* Van Hise, "Treatise on Metamorphism," Mon. 47, U.S.A. Geol. Surv., p. 341.

† Op. cit., p. 227.

8.—ORIGIN OF CERTAIN CLOTS IN THE DYKES.—METAMORPHIC DIFFERENTIATION.

Though we have determined the origin of the amphibolite dykes, there remains for explanation the curious schlieren of biotite which were found in two dykes and were mentioned in the field characters. These appeared like segregations in the dykes and could be completely surrounded by the apparently normal dyke rock, though there were no sharp boundaries. Schlieren of chlorite and epidosite were found in similar circumstances (fig. 5). In each of these three cases the schlieren occur within portions of sharply walled dykes. At first sight these seem to find explanation by postulating primary magmatic xenoliths, composed possibly of augite or olivine, whose individuality has been preserved throughout the metamorphism.

We consider first the biotite schlieren. One of the biotite schlieren, No. 4 (Plate II., fig. 6), has been found to possess the following mineral composition :—

Biotite	64·9
Hornblende	32·2
Quartz	1·7
Muscovite	0·6
Lawsonite	0·4
Epidote	0·2
Apatite, Sphene	present

The rock is highly schistose and shows a number of angular folds. The angle made by the sides of the folds is 30°. The biotite forms practically two-thirds of the rock, while hornblende nearly completes the remaining third. The biotite is brown, well crystallised with numerous pleochroic spots. Epidote is only rarely associated with the biotite. The hornblende is intergrown in parallel position with the biotite, and cross sections are idioblastic against the biotite. It has a more pronounced prismatic habit than in the normal amphibolites. Its colour is different and appears to follow the scheme—X very pale yellowish green, Y green, Z bluish green. The colour is not so intense as usual, indicating less iron in its composition. The hornblende only rarely contains inclusions of quartz, apatite, or sphene. A small amount of biotite is replaced by colourless muscovite, and occasionally the biotite is intergrown with lawsonite. Quartz is irregularly distributed, but rather seems to concentrate in the axes of the miniature folds.

The chemical composition of this rock is found by J. C. Watson to be—

SiO_2	43·12
Al_2O_3	12·74
Fe_2O_3	1·35
FeO	10·14
MgO	17·13
CaO	4·70
Na_2O	0·26
K_2O	6·08
H_2O +	3·07
H_2O −	0·02
CO_2	nil
TiO_2	1·35
P_2O_5	trace
SO_3	nil
Cl	0·06
MnO	0·13
NiO, CoO	trace
CoO	p.
Li_2O	nil
Total	100·15
Sp. Gr. at 4° C.	3·012

If this composition is compared with that of the normal amphibolite, No. 629, strong points of difference are noticed, and these correspond with the mineralogical differences. There is 5 per cent. less silica, but the most striking differences are found in the percentages of CaO, MgO, and K_2O, and Na_2O. The amount of K_2O is more than seven times greater, and the Na_2O about seven times smaller. There is two and a half times as much MgO, while the CaO has decreased by a half. The large percentages of MgO and K_2O correspond with the high percentage of biotite. There is no important difference in the alumina, total iron, or titanium.

The Ozann group values are— S = 4·60, A = 4·3, C = 3·5, F = 37·4, M = 1·8, T = 0, K = ·6.

The projection values are— $a = 1{\cdot}9$, $c = 1{\cdot}5$, $f = 16{\cdot}6$.

These values, considered collectively, place the rock among the magnesium silicate schists, Group V., though the high value of A is exceptional for this group. The position in the triangular diagram is shown in fig. 6.

The composition of these biotite hornblende schlieren seems impossible for any primary magmatic xenolith that can be postulated. Neither augite nor olivine can yield the high potash percentage of biotite, and, if we postulate sufficient felspar to supply the alkali, there would be insufficient magnesium or iron for the hornblende and biotite. If we ignore this difficulty and still assume an augite xenolith, we raise further difficulty in recalling that hornblende, or biotite with epidote, is the normal metamorphic equivalent of augite in this series. The amount of epidote in this schliere is scarcely appreciable.

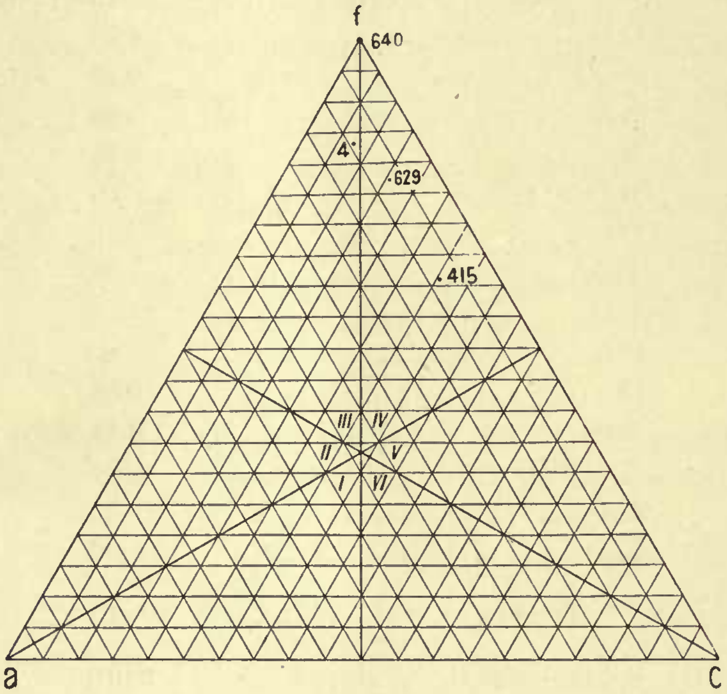

Fig. 6.

629. Amphibolite, Cape Denison.
640. Chlorite schist, Cape Denison.
415. Epidosite, Cape Denison.
4. Biotite hornblende schist, Cape Denison.

The original dolerite may have contained some biotite and, therefore, it might be conceived as possible that the schlieren are the metamorphosed equivalent of primary segregations composed of two-thirds biotite and one-third augite. Such would be a very extraordinary xenolith, and I am not aware that we have any information of such a type of cognate xenolith. Here it is quite apt to remark that it is fundamentally wrong to insist on explaining curious metamorphic features by reference to abnormalities in the primary rock, igneous or sedimentary. The biotite and the hornblende throughout the series have been developed during the metamorphism, and it is quite reasonable to view these schlieren as true metamorphic products. The beautiful parallel arrangement of the biotite and the hornblende strongly suggests that this rock owes its origin to the metamorphism and nothing else.

A biotite schliere is recorded in the band from which specimen No. 630 was collected as the normal rock of the band. The schliere occurred in a broad bulge 12ft. or 15ft. wide, and No. 630 was picked up not more than 2yds. or 3yds. away from it. Unfortunately there is no example of this schliere in the rock collection, but it is quite certain from its soft character that it contained a large percentage of biotite. Another specimen (No. 630A), however, was obtained from this spot which is also of curious composition. It is coated with black biotite, but it is hard and contains a good deal of felspar. The rock is not of such even composition as the biotite hornblende schist. The felspar occasionally appears as a porphyroblast, or tends to aggregate and form lighter coloured patches. The mineral composition of the ground mass of this rock, determined in a section cut at right angles to the schistosity, is—

Biotite	44·4
Felspar	51·8
Epidote	2·8
Apatite	1·0

Sphene and magnetite present but less than ·1.

The rock is, therefore, essentially an aggregate of biotite and felspar. The specimen shows a certain amount of mechanical deformation, but this again is subsequent to the development of the biotite and felspar. Some of the biotite is twisted and shows attrition, while some of the felspar is granulated. The felspar is andesine, and a portion is saussuritised. This saussuritisation may have developed in the subsequent crushing. The epidote crystals commonly contain a core of allanite. Quartz is absent. The mineral composition bears some resemblance to that of the band No. 153 (Table I., No. 1). In this case there is no hornblende or sphene and less epidote but more felspar and biotite. We can, therefore, picture its chemical composition with more silica and alkalies and less FeO, MgO, and CaO than No. 153 (p. 21). It is thus certain that the composition of No. 630A, as well as the composition of the biotite hornblende rock No. 4, differs considerably from that of the normal amphibolite. The conclusion is unavoidable that there has been a rearrangement of chemical composition during metamorphism.

The composition of No. 630, the supposed normal rock of this band, is also abnormal. Table I., No. 6, shows that the colourless constituents in No. 630 are double those in No. 412, an example to which it is otherwise strikingly similar. This large excess in No. 630 is due to the numerous grains of clear, uncrushed quartz, a mineral which is nearly absent in all the normal bands. The microscopical structure of this quartz is essentially different from the quartz in the adjacent granodiorite gneiss. Whereas the latter shows abundant cataclasis, strain polarisation, and participation in the mortar structure, the quartz in the amphibolite is perfectly clear, uncrushed, and with strain polarisation weak or absent. In other respects the minerals in No. 630 are similar to the minerals in the biotite amphibolite, No. 412. The abnormal percentage of quartz seems to me to be connected with the abnormal formations of the biotite hornblende schliere and the biotite felspar rock. From evidence which will be given later, we might look upon the biotite felspar rock as a metamorphic hybrid produced by the intermingling of gneiss and amphibolite in the solid state, because a fragment of gneiss may readily have been caught up in the injection of the dyke. But in the case of the biotite hornblende rock we must picture during metamorphism a transference of material which results in the formation of segregations within the dykes. The formation of a segregation is equivalent to a differentiation *in situ*, which we propose to refer to as " metamorphic differentiation."

On such a hypothesis we find a ready explanation for the schlieren of chlorite and epidosite. These two schlieren occurred in the same broad outcrop from which No. 629 and the meta-xenoliths were collected. In size they are less than 2ft. in their longest direction. It has been observed from Table I., No. 7, that No. 629 is abnormally low in mica, and this fact can be correlated on this hypothesis with the observed segregation of chlorite. Microscopical examination shows that the chlorite rock is composed entirely of chlorite except for a few very minute grains of magnetite and quartz. The chlorite is green in colour, with very low polarisation colour, but it does not show the blue interference colour common with penninite. In contrast to the biotite hornblende schlieren, the chlorite rock has an approximately massive structure like its host. Further, it is to be noted that where the dominant mica is biotite in the No. 630 band, the mica schliere is composed of biotite. In No. 629, where the dominant mica is chlorite, the mica schliere is composed of chlorite, yet the outcrops of Nos. 630 and 629 are less than 40yds. apart.

The schliere of epidosite occurs 2yds. away from the schliere of chlorite. Its shape tended to be rounded and, like the previous schlieren, no boundaries against the amphibolite were observed. The hand specimens of the epidosite are massive, and the mineral composition of a thin section is—

Felspar	28·4
Epidote	65·1
Hornblende	2·5
Sphene	3·8
Iron ore	0·2

Biotite, chlorite, and apatite are present.

The thin section is illustrated on Plate II., fig. 5. The proportion of felspar is very close to the felspar percentage (27·3) of the amphibolite host No. 629, and its character is the same. The hornblende of the amphibolite is almost completely replaced by epidote in this rock. The epidote is well crystallised, has well-developed cleavage, and its characteristic pleochroism. It may contain inclusions of ragged hornblende, and it can also be observed replacing relic hornblende crystals. The transition is almost complete, but examples can be found where irregular remnants of hornblende with optical continuity are scattered through an epidote crystal. If cleavage be observed in one relic fragment, it is also observed in the associated group. The hornblende possesses a stronger bluish-green colour than in the normal amphibolite, and cross sections still exert their form against the epidote. Sphene is very prominent, and large crystals may be included in the epidote. Rarely fragments of biotite with alteration to chlorite are found in the epidote. The iron ore consists of magnetite with alteration to hematite.

The results of the analyses of the chlorite rock and the epidosite made by J. C. Watson in the Victorian Geological Survey Laboratory are as follows :—

	I.	II.	III.
SiO_2	24·96	45·49	25·40
Al_2O_3	20·76	19·50	22·80
Fe_2O_3	3·24	9·13	2·86
FeO	21·86	0·64	17·77
MgO	18·18	0·45	19·09
CaO	nil	16·88	nil
Na_2O	nil	2·66	nil
K_2O	nil	0·30	nil
H_2O +	11·45	0·08	12·21
H_2O −	0·19	1·25	
CO_2	nil	nil	
TiO_2	0·20	2·29	
P_2O_5	nil	0·87	
SO_3	tr.	tr.	
Cl	tr.	0·02	
MnO	0·05	0·05	0·25
NiO, CoO	tr.	0·02	
CoO	nil	nil	
Li_2O	nil	st. tr.	
F	—	—	tr.
Total	100·89	99·63	100·38
Sp. Gr.	2·938	3·118	2·835

	Group Values.							Projection Values.		
	S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
I.	29·4	0	0	56·3	0	0	0·5	0	0	0·20
II.	53·9	3·2	9·9	19·9	10·8	0	0·9	1·9	6·0	12·1

I. Chlorite rock. Cape Denison.

II. Epidosite. Cape Denison.

III. Chlorite. Washington, D.C. "*Rock Minerals.*" *Iddings, p* 472.

Both these analyses are again very different from that of the amphibolite host. The analysis of the chlorite is very close to that of a pure chlorite, as is seen by comparison with the analysis of a prochlorite quoted from Idding's "Rock Minerals." Its group values place it among the chlorite schists, Group V., though the projection values do not separate the rock from the magnetite schists of Group XI.

The very high values of FeO and MgO in the chlorite rock are notable in comparison with the very low values in the epidosite, while the reverse is true with regard to CaO. The total lime and magnesia is practically the same in the epidosite and in the amphibolite, No. 629, and not much different to the magnesia percentage in the chlorite rock. The total alkalies in the epidosite are also approximately the same as in the amphibolite, with a large excess of soda in both cases. The latter point corresponds with the observed fact that the amount of felspar is the same in both rocks, and that the formation of the epidosite occurs with the replacement of hornblende by epidote. There is also a notable increase of titanium in the epidosite, corresponding to the increased percentage of sphene in the epidosite.

All the group values of the epidosite, except M, agree with those of Group IX., the lime silicate rocks. But though the value of M is below the stated limits for this group, there can be no doubt that this epidosite should be included in the group of epidosites which appear in the epi division of Group IX.

The projection values of these two rocks are plotted in fig. 6, and it is to be noticed that they fall symmetrically on either side of the position of No. 629.

Hence from the microscopical and chemical study of these rocks we consider that the epidosite has been derived from the amphibolite during the recrystallisation, and not from a pre-existing magma clot. The same is no doubt true of the chlorite rock, and the conclusion is again forced upon us that there has been chemical migration and rearrangement during metamorphism. It is the type of exchange that we intend to refer to as metamorphic differentiation.

Geological literature provides many examples where epidosites have been observed in association with amphibolites or hornblende schists. In one instance in the Lizard area Flett has supposed them * to be due to chemical segregation during metamorphism, and our conclusion is a similar one.

If one still urges that the biotite hornblende schlieren may be the result of metamorphism of a primary igneous xenolith in a dolerite dyke he is now confronted with the difficulty of explaining why the schlieren have the composition of biotite hornblende in one place, of biotite felspar in a second, of chlorite in a third, and of epidosite in a fourth. Finally he must explain why these four types of schlieren appear as primary metamorphic products, and yet are all essentially different from the relics of the primary cognate and accidental xenoliths that have already been described from the same outcrop of No. 629.

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* "Geology of the Lizard and Meneage," Flett & Hill, p. 50.

We cannot at present indicate the conditions which permit metamorphic differentiation in localised portions of certain bands, while the majority of bands remain undifferentiated. The conditions may possibly arise from some combination of solid diffusion with that force of crystallisation of the specific mineral which determines its position in the crystalloblastic order. If it be objected that solid diffusion is a process of much too limited range, and of too infinitesimal a rate, then it must be remembered that the whole record of geological time is available. The presence of water may be an assisting factor—it is necessary material in the formation of epidote and chlorite—but we cannot assume mere migration by solution while we insist that the formations occurred under the influence of strong stress. We can only surmise that the points of metamorphic differentiation have in some way been the focus of special conditions of stress or uniform pressure which, combined with other special mineral forming conditions, have caused an abnormal development of that special mineral. A condition of relatively low hydrostatic pressure and stress might, on the one hand, permit the more ready transfer of molecules; but, on the other hand, a condition of low hydrostatic pressure and strong stress might favor the process of solid diffusion.

Metamorphic diffusion and differentiation are essentially processes of limited range. They occur in a rock which is, to all intents and purposes, solid, and molecular movement is hindered. Their products can never attain the dimensions of the products of magmatic differentiation.

9.—Description of the Coarsely Crystalline Basic Patches in the Granodiorite Gneiss.

Apart from the well-defined series of metamorphosed dykes that have just been described, there exist a number of outcrops of hornblendic rock whose origin has only become evident on investigation. In the field the dykes are distinct in that they have maintained their sharp junctions and their linear trend, even though their surface outcrop may be broken. The hornblendic rocks now under consideration present a contrast and have scarcely any definite shape, and appear as irregular dark-coloured clots in the grey gneiss. They possess a rough lenticular outline and tail out in the direction of foliation, but the boundaries may be indefinite when the dark rock passes gradually out into the grey rock. These dark rocks are often characterised by a uniformly coarser grain and the average diameter of the mineral grains may reach one and a half times that in the normal amphibolites. The rock type is not constant, and one may find patches of almost pure hornblende rock, or massive amphibolite or hornblende and biotite gneisses, which may pass through varying stages into the normal granodiorite gneiss. Sometimes one can macroscopically distinguish brown sphene crystals up to ⅛in. long as well as pyrite or magnetite.

The indefinite boundary, the coarse granularity, and a relatively massive texture suggested in the field that they would yield evidence of primary consolidation of the same nature as the granitic rock. Later study, alone, has shown that the coarse granularity has been produced by secondary or metamorphic crystallisation, and that they are indeed a part of the dyke series. Hence a revised study of the field relations would have been profitable had circumstances permitted it. Small examples of basic schlieren can be seen in the illustrations of polished rock (Plates XVIII., fig. 1; XXII., fig. 2).

Petrographical Characters.

We deal in detail with three examples of this type which bear the field numbers of 9, 13, and 10. No. 9 belongs to the massive type, and Nos. 13 and 10 to the schistose types. These specimens were collected from hornblendic patches which passed by transition into normal gneiss. Rosiwal measurements have been made of thin sections of these rocks in the same manner as before, with the following results:—Columns 13A and 10A are the recalculated compositions of Nos. 13 and 10 when the quartz has been disregarded.

	No. 9.	No. 13.	No. 13A.	No. 10.	No. 10A.
Quartz	—	29·2	—	23·4	—
Felspar	23·1	22·2	31·4	34·3	44·8
Mica	10·7	15·0	21·1	32·2	42·0
Hornblende	61·8	31·9	45·1	—	—
Epidote	1·8	1·7	2·4	7·6	10·0
Sphene	2·6	p.	—	0·8	1·0
Iron Ore	—	—	—	0·7	0·9
Apatite	p.	p.	—	1·0	1·3

No. 9.—The specimen was collected near the magnetograph house. It is dark, massive, coarse grained, showing abundant platy hornblende and dull felspar. Grains of pyrite and sphene are occasionally seen.

In thin section the rock is coarse and granoblastic. The average absolute grain size of the hornblende is approximately 1·5mm.; but in other specimens from the same locality the hornblende crystals are as much as 4mm. and 5mm. broad. Hornblende, which forms nearly two-thirds of the rock, is found in granular crystals without terminal faces. The prism faces and cleavage are well developed as usual. Its colour scheme is—X greenish yellow, Y bright green, Z bluish green. It contains abundant inclusions of biotite, sphene, ilmenite, and epidote. Parallel strings of small sphene inclusions are common in sections parallel to the cleavage.

The 23·1 per cent. of felspathic material forms the colourless constituents of the rock, and consists partly of turbid saussuritised felspar and partly of clear felspar. The saussurite yields a brightly polarising aggregate which, under close examination, opens up into mica, epidote, chlorite, and clear felspar. There are no traces of cataclasis. The clear felspar is less in amount than half the total felspar. Part is untwinned and part possesses both albite and pericline types of lamellar twinning. A simple twin with lamallæ in both halves was found to give extinction angles of 14° in one set and 15° in the other set. Hence we designate the clear felspar albite.

The biotite is well formed and often appears as inclusions in the hornblende. It is mainly the normal brown biotite, but it is often intergrown with a green biotite. Some of the green appears to be chlorite, and normal chlorite with its low, anomalous blue polarisation colour is present in the section. The brown biotite seems to be developing from the green biotite, which in turn comes from the biotite. The biotite and chlorite appear under one head in the quantitative statement, as it is not always possible to assert the line of demarcation. Sphene is relatively abundant, and some grains are comparable in size with the hornblende, while others are minute inclusions in the hornblende. Most grains are anhedral, and only a few possess the characteristic wedge-shaped outline. Pleochroism is strong in thick sections, and many of the crystals possess a magnetite nucleus. As almost all the magnetite occurs in this manner, the sphene-magnetite individuals were treated together in the Rosiwal measurement. In some cases the rim of sphene is made up of a number of sphene grains with different optical orientation. Some of the iron ore is ilmenite, as it is associated with its whitish alteration product, leucoxene, but when the leucoxene recrystallises as sphene, the ilmenite may change to magnetite. Occasionally there is a reddish-brown mineral which is taken to be rutile. Epidote appears in colourless or honey-yellow pleochroic grains. It is sometimes included in the hornblende, sometimes interlaminated with biotite, and sometimes found as individual grains surrounded by the felspar decomposition products. Pyrite in small scattered cubes and apatite are present.

The rock is thus seen to correspond very closely with the description of a typical amphibolite of the dyke series. The same type of hornblende, the same saussuritised felspar, and the same clear felspar, and also the same peculiarities of the mica are found in both cases. The quantitative expression of the mineral composition is now valuable for comparison with the mineral compositions of the amphibolite dykes in Table I. The composition of No. 9 is quoted in Table I. for this purpose. The strong similarity towards types like Nos. 631 and 635 becomes obvious, and as the texture of No. 9 is approximately massive, any error due to the schistosity is very small. The felspar content is the smallest of the series, but only by a very small amount; but the hornblende percentage is the same as a normal amphibolite, and so also is the mica. The mineral composition is therefore quantitatively as well as qualitatively essentially the same as a normal amphibolite with dominant hornblende produced in the metamorphism of a dolerite dyke. The chemical composition must also be the same. Specimen No. 9 is therefore identical in kind with the examples of the undoubted dykes series, and the conclusion is unavoidable that it is part of the same series. The apparent difference is due to the fact that secondary crystallisation has proceeded under more favorable circumstances and larger crystals have been formed. This larger granularity signifies nothing in primary origin.

No. 13.—Specimen No. 13 is a transition type, and was collected from a similar outcrop to No. 9, but a linear trend was more noticeable. Its boundary with the gneiss is indefinite. It is a rock with much the same granularity as the typical granodiorite gneiss, and this is larger that that of the average amphibolite. Its colour is intermediate between the black amphibolite and the grey gneiss. A coarse crystallisation schistosity is rendered prominent by dark bands of hornblende and white bands of felspar and quartz. This schistosity, of course, reduces the accuracy of the statement of the mineral composition in Table II.

In thin section we find the schistose bands consist of quartz, of hornblende with biotite and epidote, and of saussuritic aggregates. The hornblende is identical in type to that of No. 9. Chloritisation of the hornblende is not uncommon. Biotite is associated with the hornblende bands, and is found with both a green and a brown color, interlaminated together as before. The brown is more abundant than the green, which is again an intermediate stage between green chlorite and brown biotite. Epidote is very frequently associated with biotite, and is illustrative of a previous conclusion that biotite and epidote are equivalent zonal products of hornblende, and that the biotite appears when there is a supply of potash. The epidote expressed in the quantitative statement in Table II. is that amount of epidote which occurs in this association. A larger amount of epidote appears among the cloudy saussurite, and has been included therein in the measurement.

The felspar percentage expresses the amount of saussuritic aggregates which include all the cloudy material under the low power objective. Some of the cloudy parts remain dense and unresolvable. Part, however, can be resolved into epidote and a colourless well-formed mica, which is possibly paragonite. Most of this epidote is in fine granular aggregates. Clinozoisite or zoisite is also present. The colourless mica shows strong absorption, and is similar in appearance to muscovite. Rough measurement has indicated that it forms at least one-ninth ($\frac{1}{9}$) of the saussuritic aggregates, and since the primary felspar is here as in previous cases a calcic plagioclase, we cannot refer it to a potash mica without providing a source for the potash and a means of escape for the soda. The aggregates consist chiefly of epidote and colourless mica, with some chlorite and biotite. No secondary clear albite has been determined with certainty, and quartz grains appear among the cloudy masses, and hence the colourless mica may have absorbed the soda from the felspar. The percentage of biotite is considerable, and this means an absorption of considerable potash. It is reasonable, therefore, to strongly suspect the presence of paragonite mica.

Quartz is abundant, and provides the chief distinguishing feature from the typical amphibolites. Entering as it does into the crystallisation schistosity it cannot be looked upon as a quartz-veining subsequent to those processes which impressed the rock with the individuality of the schist. It is as essentially part of the schist as the hornblende layers or the saussurite layers. It is clear, and the larger grains invariably show strain polarisation. The grains are interlocking, and not infrequently possess a lenticular shape due to solution at the points of greatest pressure and simultaneous deposition at points of minimum pressure. It is quite different in character to the quartz in the granodiorite gneiss. Apatite is an accessory mineral. Reddish hematite occurs among the saussurite, but grains of magnetite are scarce. The rock may be named an hornblende gneiss.

The quantitative expression of this mineral composition in Table II. emphasises the difference between No. 13 and No. 9. Marked as this difference is, the microscopical description brings forward points of resemblance. The hornblende and mica are similar in both cases, and the saussuritised felspar is quite abundant considering the high silica percentage of the rock. If we neglect the quartz and recalculate the mineral composition we obtain 31·4 per cent. felspar, 21·1 per cent mica, 45·1 per cent. hornblende, and 2·4 per cent. epidote. Then we find that the proportion of felspar (saussurite) to the ferromagnesian (hornblende and mica) is very similar to that of the typical amphibolites. Yet, in appearance and in the abundant quartz it possesses some likeness to the granodiorite gneiss. The examination of this rock, therefore, provides microscopical evidence to support the field observation that there is a gradual passage from this basic patch into the enveloping granodiorite gneiss.

No. 10.—Specimen No. 10 is a different type collected from the same small area as No. 13. Glistening biotite is abundant on the cleavage surfaces, but nevertheless the rock has a tendency to a massive texture as a result of its very fine-grained character.

In thin section the rock consists of biotite, saussuritic felspar, clear felspar, quartz, epidote, apatite, magnetite, and zircon. The biotite is the pale brown variety and has a noticeable parallel arrangement. Scattered patches of chlorite may be found which are often accompanied by iron ore. The felspar consists of twinned and untwinned felspar and cloudy saussurite. The quartz shows considerable cataclasis and strain polarisation effects. It appears as parallel layers in the section conformable with the layers of saussurite and biotite. The grains are clear except for occasional inclusions of apatite, and there is a noticeable absence of the linear inclusions that appear in the quartz of the granodiorite gneiss. Epidote is relatively abundant and sometimes forms large well-shaped individuals and sometimes it is finely granulated. It is frequently included in the biotite, but the finely granular epidote may form a rim to a biotite crystal. Sphene and apatite are accessory minerals and ilmenite is present in occasional large crystals. Hornblende is absent. The rock may be described as a biotite gneiss.

The quantitative mineral composition is expressed in Table II. In the large percentage of quartz it resembles No. 13; but this percentage is lower than that of No. 13. It is not expected that these percentages would show any other similarity than correspondence between two extremes. The ferromagnesian total, however, is not much different. We notice again the sympathetic variation of the percentages of biotite and epidote.

If we assume, as in the preceding case, that silica is the chief mineral addition to the original dyke rock, and the mineral composition be recalculated to 100 per cent. after neglecting the quartz, we obtain the figures in column 10A. These figures bear some resemblance to the composition of No. 153, in Table I. The proportion of felspar to ferromagnesian is much the same in both cases; but the felspar of No. 10 is nearly all saussurite, whereas the felspar of No. 153 is perfectly clear. No. 10 thus appears to be related to the epidote biotite schists in the same way that the hornblende gneiss No. 13 is related to the normal amphibolites.

10.—Origin of the Coarsely Crystalline Basic Patches.

The origin of these dark hornblendic and biotitic rocks which are enveloped in the granodiorite gneiss, and which have been designated the coarse-grained types, is a very interesting question. It has been shown that the massive amphibolite from these patches is identical, except for larger grain size, with the amphibolites which have been established as altered dykes. It is also plain that there is true transition from this amphibolite through hornblende gneiss or biotite gneiss to the granodiorite gneiss. Accepting the face value of these gradual transitions, we might say that these "basic" patches have been derived out of the granodiorite itself. We might conceive of a magmatic differentiation which was initiated in the granodiorite magma which became frozen before the differentiation process was complete. A sudden cessation of the differentiation forces has left a gradual apparent transition between the amphibolite and the granodiorite. Such an argument completely ignores the observed similarity of the textural, structural, mineralogical, and chemical relations of related rock types at Cape Denison, and at the same time we miss the recognition of a true metamorphic process.

Since the coarse-grained type is so precisely similar to the amphibolite dyke series which has been proved to be the metamorphosed equivalent of diabasic dykes, it is extremely likely that the No. 9 type of amphibolite has been derived from a primary rock of similar nature. They occur approximately along the extension of well defined dykes, and hence it is extremely likely, and as definite as it is possible to be, that the primary rock of the No. 9 type was part of the intruded series of dykes. We have described fragments of the dyke series proper which have been torn away from the dyke channel and now appear completely enclosed in the gneiss. Discontinuity of the hornblendic clots, irregularity or isolation are, therefore, matters of little weight. These detached fragments of the established dykes have escaped the more intense metamorphism which produced the larger grain size of No. 9, and they have been able to preserve their sharp outline against the gneiss.

There is no special reason, however, why a pre-existing junction between two rock types must be preserved during metamorphism. We have maintained in our hypothesis of metamorphic differentiation that a limited migration may occur in the solid rock under special conditions of metamorphism. If such migration occurs across a pre-existing junction there must, *a priori*, be a strong tendency to efface that junction. If we imagine a diffusion of some of the amphibolite material into the granodiorite gneiss, or some of the gneissic material into the amphibolite, we would get the former junction replaced by the gradual transition observed. The transition types would be mixtures of amphibolites and granodiorite gneiss, and would correspond to the types No. 13 and No. 10. Such a theory is in agreement with the observations, and we will speak of the process, for convenience, as metamorphic diffusion. Diffusion products, like the hornblende and biotite gneisses, are, therefore, looked upon as metamorphic hybrid rocks.

Solid diffusion has been suggested before to account for the perfectly gradual passage of granitoid rocks into surrounding schists. Greenly* endeavoured to compare such phenomena with the laboratory experiments of Roberts-Austen on the diffusion of gold into lead. Greenly, however, postulates a mixing of a granite magma and the neighbouring sedimentary rocks, a conception which involves not true solid diffusion, but merely a mechanical percolation of the surrounding schists by highly fluid magma. Desch† therefore pointed out that the term " diffusion " had been loosely employed. Another claim for solid diffusion is mentioned by Elsden‡ in the observations of Trener on the contact phenomena of Cima d'Asta, but the same objection again holds. While it has been usual in these cases to suppose that the mixing takes place at the time of intrusion, I do not know of evidence to show that a degree of mixing has not occurred after complete consolidation; and, if this is so, these cases may be examples of solid diffusion.

The difficulty lies in the proof of the solid nature of the rocks before the mixing. At Cape Denison the granodiorite must have been solid before it could be fractured and penetrated by the primary dolerite dykes; and the presence of the meta-xenoliths in the amphibolites indicates the consolidation of the dykes before their metamorphism. Further, we cannot suppose that a thin sheet of dyke magma would remain fluid for a sufficient length of time to permit the mechanical percolation that is possible in the case of a large, deep-seated, slowly-cooling plutonic mass. Hence at Cape Denison we consider that solid diffusion, in the strict sense of the term, has operated. The term " metamorphic diffusion " implies that diffusion has occurred in the solid state.

Metamorphic diffusion is not restricted to the amphibolite gneiss junction at Cape Denison. It also appears along the junction of the aplitic gneisses with the granodiorite gneiss. The examples quoted tend to show that quartz is a mineral that is readily diffused, but other mineral molecules like hornblende and biotite can be so transferred.

Basic segregations are common in many granitic masses and may be relatively rich in either biotite or hornblende. If these were recrystallised under conditions permitting metamorphic diffusion it may be imagined that hybrid rocks, similar to the hornblende and biotite gneisses, might arise. Consequently such types may possibly be discovered in isolated masses in regions where there are no traces of the existence of dykes. At Cape Denison, however, the evidence seems clear that they are connected with dykes.

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* " Diffusion of Granite into Schists," Greenly, Geol. Mag., vol. 10, dec. 4, N.S., p. 207.

† " Report on Diffusion in Solids," C. H. Desch, Brit. Ass. Report (Dundee, 1912), p. 348.

‡ " Principles of Chemical Geology," J. V. Elsden, p. 2.

It will be subsequently shown that the most intricate dyke structures can be preserved during the metamorphism at Cape Gray, where the recrystallisation has occurred under kata zone conditions, in which the pressure factor is chiefly hydrostatic. At Cape Denison the pressure factor in the metamorphism is chiefly stress, and hence the destruction of the dyke structures and the migration of material is to be connected with the dominating stress.

11.—Further Examples of Metamorphic Diffusion.

Junction Specimens.

The above interpretation of the biotite gneisses as metamorphic hybrid rocks, produced by an intermingling of two diverse rock types by solid diffusion, is upheld by the examination of specimen No. 372, found on the moraines at Cape Denison. This specimen was collected as a diagrammatic example of the normal "sharp" junction between the amphibolite and the gneiss. One-half of the specimen (Plate XII., fig. 5) is black amphibolite, and the other half is grey granitic gneiss. The junction, however, is not sharp, and how far this applies to all the dyke junctions at Cape Denison is not known. As the specimen was not found *in situ* it is not possible to assert that the amphibolite represents a portion of a dyke originally intrusive into the granitic gneiss. But as both the amphibolite and the gneiss are analogous to specimens found *in situ* it is very probable that such is the case.

In a section of the granitic portion of the specimen it is found that the cataclasis, so marked in most of the typical granodiorite gneisses at Cape Denison, is absent. The epi zone metamorphism, however, is signified by the amount of saussuritised or sericitised felspar and by the chloritisation of the biotite. The amount of ferromagnesian minerals is less than in the typical example No. 11, but it is not noticeably less than in other examples from Cape Denison. In addition to the cloudy felspar there is a considerable quantity of clear, recrystallised felspar which, with the quartz, possesses the crystalloblastic structure. Some of the clear felspar is untwinned, but some of the twinned crystals have been determined to be oligoclase-andesine. The biotite is brown, but is largely altered to green chlorite. There is in addition scattered epidote, allanite, lawsonite, pyrite, and apatite. The general characters and the composition of the felspar indicate the relation to the granodiorite gneisses.

A section across the junction reveals the presence of a zone of biotite gneiss, approximately 1 c.m. wide, between the amphibolite and the granodiorite gneiss. The transition from the latter into the biotite gneiss is fairly rapid. There is no variation in grain size or in structure or configuration of the crystal grains across the apparent junction. The zone of biotite gneiss consists of abundant brown biotite set among grains of clear felspar, cloudy felspar, and quartz. The character of the plagioclase is the same as in the gneiss. There is less quartz in the biotite zone than in the grey gneiss, and plagioclase occupies a greater percentage of the colourless material. Epidote is practically absent.

The transition from the zone of biotite gneiss to amphibolite is more gradual than its passage into the granodiorite gneiss. In the amphibolite the hornblende largely replaces the biotite, but the relative amount of biotite is probably sufficient to call the rock biotite amphibolite. The hornblende has, on the average, a larger grain size than the biotite, but its character is quite similar to the hornblende in the amphibolite dykes. Quartz still appears in small pieces in the hornblende area; but by far the greater portion of the colourless constituents consists of saussuritised felspar. A little lawsonite is intergrown with the biotite.

In this case it is perfectly clear that a zone of biotite gneiss has developed along the contact between granitic gneiss and amphibolite. But it has not been produced by simple contact metamorphism, nor by assimilation, and we believe that it is another example of a metamorphic hybrid produced by solid diffusion.

No. 160 is another specimen from the moraines (Plate XII., fig. 6) which is diagrammatic of the manner in which the black amphibolites cut the granitic gneiss. In this case the gneiss is more basic than the Cape Denison granodiorite gneiss. Though there is still abundant quartz in it, labradorite has been identified among the plagioclase and hornblende is much more abundant than biotite. It may be distinguished as a hornblende gneiss. The amphibolite consists of hornblende and plagioclase with a little biotite. Though the granoblastic structure is noticeable on both parts of the rock, the junction is a line of interlocking crystals and is comparatively sharp.

Composite Gneiss.

We have now to consider areas at Cape Denison in which the amphibolite bands seem to open out into a series of thin parallel threads interwoven with the granodiorite gneiss. The boundaries of the threads are often indefinite, so that some doubt existed in the field as to whether they were related to the amphibolites. These are areas of composite gneiss. A specimen (No. 144) from one of these thin interwoven bands is a dark-coloured massive rock, a little coarser than the normal amphibolite. The hand specimen shows abundant glistening biotite and small felspar porphyroblasts are distributed through it.

In section it is found to be a crystalline aggregate similar in type to the biotite felspar gneisses, No. 630A and No. 10. It consists chiefly of biotite and felspar in much the same proportion as in No. 630A. Epidote is often associated with the biotite, and there is a subordinate amount of quartz; sphene, apatite, magnetite, and pyrite are present. The felspar is nearly all perfectly clear, and in some cases two sets of lamellar twinning are beautifully developed, especially in the porphyroblasts. The maximum extinction angle that has been measured is 16°, and the refraction is very close to, but always less than, nitrobenzol (1·551). It is always above nelkenol (1·542). We, therefore, consider it to be an oligoclase-andesine. The brown biotite shows very little change to chlorite.

In the amount of biotite and in the complete absence of hornblende this rock is similar to the previous transition type, No. 10, and to the biotite zone described in the junction specimen No. 372. There is much less quartz in this case than in No. 10, while clear felspar replaces the cloudy felspar. There is more epidote than in the No. 372 example, but it is very likely that this rock has a similar origin and is a product of metamorphic hybridisation.

There can be no doubt that the clear character of the felspar is due to the metamorphism, and the size of the crystals has, therefore, no great significance. There is, in fact, considerable variation in the size of the felspars from the same locality as No. 144. In specimen No. 146·1 the average size of the felspar is about equivalent to the porphyroblasts in No. 144 (Plate XII., figs. 1, 2, and 3), but the mineral composition of the rock is similar to that of No. 144. In specimen No. 146·2 there is a still greater development of the felspars; but in this case there has not been a uniform development and some crystals are much larger than others. In the hand specimen there is a suggestion of a brecciated appearance, but in section there is no evidence at all of crushing or cataclasis. No variation in the constituent minerals in the different specimens has been noticed, while the specimens were collected within a yard or two of one another.

Primary relic felspar can usually be recognised, both in the granodiorite gneiss and in the amphibolites, either by the mechanical alteration or by the saussuritisation. On this ground alone we would have difficulty in maintaining an igneous origin for the porphyroblasts. Further, as neither the amphibolite dykes nor the granodiorite is porphyritic near the particular outcrop, it is impossible to apply Cole's explanation* of the origin of porphyritic felspars in the biotitic schists, related to amphibolite, which are associated with a porphyritic granite gneiss at Barna, County Galway. In Cole's theory the felspar crystals were present in the original granite magma which threaded and penetrated the surrounding schists, increasing their SiO_2 percentage. The felspar phenocrysts, however, could not flow away and became stranded, one by one, in parallel series in the schists. In the Barna granite the large felspars are orthoclase, while in Cape Denison examples they are plagioclase; but in both cases the matrix is chiefly biotite, and the rock is related to amphibolite. In our case the origin of the large felspars is connected with the origin of the biotite felspar rock.

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* "A Composite Gneiss near Barna (County Galway)," G. A. J. Cole, Q.J.G.S. LXXI., 1916, p. 183.

Specimens (No. 145) from the same locality are in the rock collection which show the junction of the dark biotite threads with the grey granitic tongues. A dark line of demarcation exists between them in some specimens, but no sharp junction exists. In other cases (Plate XII., fig. 4), where the biotite felspar rock is seen on either side of a tongue of grey granitic gneiss, the boundaries are quite indefinite.

In sections of No. 145 there is little to indicate a junction. At one end of a section we may find biotite and felspar, with but little quartz. At the other end there may be less biotite and much more quartz, but the distribution of these constituents is not regular. No change in the character of the plagioclase is observed throughout the slide. The presence of large quartz crystals and the larger grain size of the quartzose areas are the most noticeable features of the grey rock. We are therefore dealing with a partially obliterated junction, and we can again consider, as in No. 372 and No. 10, that we are dealing with a metamorphic hybrid product produced by metamorphic diffusion. The biotite felspar gneisses are related to the amphibolites which have been produced from an intrusive rock. A supply of potash and silica from the granitic rock enables the ferromagnesian content to be expressed in biotite instead of in hornblende, as in the normal amphibolite. As a dyke disappears into the thin sheets the number of junction planes is considerably increased, and there is more opportunity for the subsequent interdiffusion of material. With this opportunity there is a greater development of the biotite felspar schist, and the intrusive features in the field become correspondingly more indefinite. Hence the thin dark threads which appear in the field to be connected with the amphibolite bands are so related, but the basic rock has been modified by metamorphic diffusion. It is not to be assumed that only the amphibolite undergoes change during the metamorphism. The granodiorite gneiss may also be modified. It only so happens that the change from hornblende to biotite is one that can be readily recognised. A change in the granodiorite, which involves a decrease in silica and in alkalies, is one that cannot be so readily detected.

No. 424.—No. 424 is another example of a biotite felspar gneiss, which was obtained from a schliere of dark rock in the granodiorite gneiss. The schliere is a few yards away from a definite band. In addition to the brown biotite and clear felspar, the rock, like No. 10, contains a good deal of quartz. Epidote is also moderately abundant, while pyrite, allanite, apatite, and sphene are present. In these accessory minerals there is a likeness to the dark amphibolites. The junction with the enclosing gneiss is not sharp, and the quartz may again have entered by diffusion. In any such isolated instance there is always a possibility that such a rock is the metamorphosed equivalent of a primary basic segregation in the granodiorite; but against this supposition there is the symmetrical relation of the schliere to the planes of foliation of the gneiss. Knowing the relations of other biotite gneisses, one would favour the inclusion of this lenticle with the amphibolite series.

No. 411.—No. 411 is another example of porphyroblastic felspars which are in this case set in a biotite amphibolite. It was found not more than 100yds. away from the area of composite gneiss from which No. 144 was taken. It occurred close to the junction plane of the dyke which was cut by a quartz segregation vein carrying large crystals of epidote. This quartz vein may have carried felspar. The specimen has a more noticeably brecciated appearance than No. 146, and whereas in the latter the felspar is white or transparent, it is here pinkish or greenish white, a colour which indicates saussurite. The outline of the crystals is not definite, and they approach to lenticles in character. In section there is no special evidence of crushing, and the large irregular felspar crystals are set in the amphibolite ground mass. The same minerals are present as in the normal rock of the band, No. 412, though the large felspar causes a preponderence of the colourless constituents. Some of the felspar is clear, and approaches andesine in character, but its refractive index is close to, but less than, 1·551 (nitrobenzol). The bulk of the felspar in the section is saussuritised. A few blebs of quartz are recognised, and there is perhaps a little more chlorite than in No. 412. As in No. 412, lawsonite is present in small amount.

The altered nature of the large felspar in this case prevents the assertion that they are metamorphic products. They may have been associated with the accompanying epidote-bearing vein, or they may be allied to the xenoliths of saussurite described from the band No. 629.

12.—Further Examples of Metamorphic Differentiation at Cape Denison.

If the amphibolite patches, which may have either sharp or indistinct boundaries, are to be included in the dyke series, we immediately find further samples of metamorphic differentiation. In the description of these coarse-grained types, reference has been made to the bands and lenses of pure hornblende associated in the field with them. That these are also part of the original diabasic magma seems evident, because we only find them in such association. We think, therefore, that we can consider these patches of hornblende in the same way as we have considered the biotitic, chloritic, and epidotic clots which are enclosed in the sharply-walled dykes. As the biotite, etc., patches are metamorphic differentiation products, so also are the hornblende patches. In the one case there has been long continued conditions for the formation of biotite, and in the other case an analogous set of conditions for the formation of hornblende. It has been noted throughout the series that the hornblende and the biotite appear as equivalent zonal products, and if we get the differentiation of one we should reasonably get the differentiation of the other. Indeed, we have already discovered this in the biotite hornblende clot. It is true in the case of hornblende that its composition may be similar to a xenolith of pyroxene crystals in the primary magma, or to an ultrabasic magma, and a hornblende patch may conceivably develop by the metamorphism of such a primary xenolith. If this were so, we should reasonably expect to find some such altered xenoliths among the sharply-defined dykes. The distribution, however, in layers conformable to the schistosity is sure evidence of at least some transference, and the frequency and variation of shape, combined with symmetry to the plane of schistosity, favour an origin by metamorphic differentiation. The neighbouring areas to the hornblende differentiates are frequently enriched in felspar when the rock assumes a lighter colour. That this hornblende differentiation only appears in the less distinctive amphibolite patches simply means that the conditions for the hornblende differentiation have been accompanied by conditions permitting metamorphic migration on a greater scale than in the biotite differentiation.

Differentiation seems to have occurred in two other basic clots. In one, No. 928, there are exceptionally large percentages of sphene and magnetite. In the section the measured percentage of sphene is 13·1 per cent. The iron is segregated in coarse crystals and, as only one or two crystals appear in a section, it is impossible to get an adequate idea of the proportion of magnetite in the rock from a single section. The magnetite crystals are as much as ½cm. broad and are abundant in hand specimen. In thin section they always possess the normal sphene rim, and in the large crystals the sphene rim is very thin. The abundant sphene crystals are large and are mostly without a magnetite nucleus. Some are twinned and some enclose biotite, but are more often surrounded by biotite. Biotite, felspar, quartz are also present in the rock. The biotite is the most abundant mineral and absorbs the ferromagnesian content. No hornblende is present, but there is a small amount of colourless muscovite. The felspar is fairly evenly distributed through the slide, but clusters of felspar crystals are noticeable in the hand specimen. The felspar is perfectly clear and colourless, but some quartz can be recognised. Small apatite crystals are abundant and there are odd grains of pyrite and epidote.

No. 928 was collected from the eastern side of Cape Denison, but coarse sphene rocks were also noticed close by the magnetograph house, the locality of No. 9. The extraordinary sphene content cannot be due to mere chance. The clot must be considered as part of the dyke series, and it would be very difficult to account for the high titanium percentage without an appeal to a metamorphic agency. The sphene and the magnetite are metamorphic minerals, and we can look upon this rock as an example of metamorphic differentiation wherein both the sphene and the magnetite contents have been enriched. The abnormal amounts of sphene and magnetite are reflected in the high specific gravity (3·10).

Specimen No. 143 is another example of a basic clot in which metamorphic differentiation has occurred. The specimen is rich in magnetite, and the magnetite crystals stand out prominently on the weathered surface. They are not quite so large as in the preceding case and can be seen to be distinctly oval in section. The longest diameter may be 4mm. and the shortest as much as 2mm. Some seem to have crystal boundaries and others are more rounded. Surrounding each magnetic bleb is a zone of white felspar, which can be plainly seen in the hand specimen and is noticeable in the photograph (Plate IX., fig. 6). Separations of magnetite were made in both this case and the preceding specimen (No. 928). In both cases tests were made to detect

TiO_2 by the reduction of HCl solution with tinfoil. A faint trace of the violet colour was obtained in the sample from No. 928, but no trace at all from No. 143. In both cases the mineral is highly magnetic, and the magnetite blebs from No. 143 were found, when suspended by a silk fibre, to possess polarised magnetism.

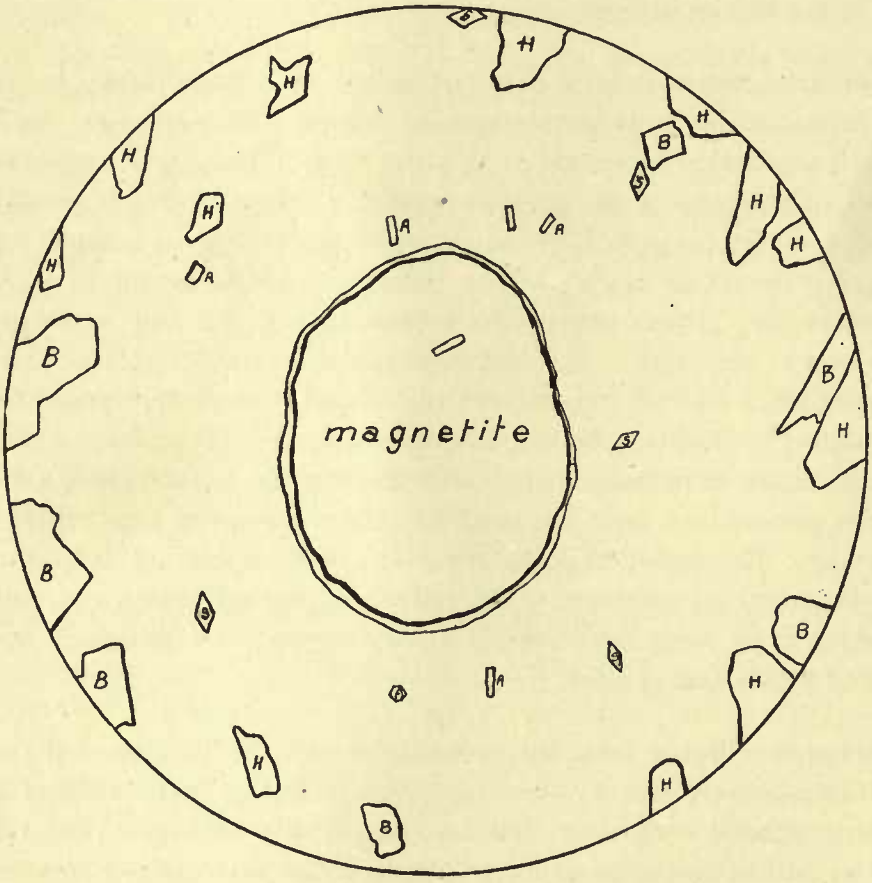

Fig. 7.

Sketch of a nodule in the amphibolite No. 143. A crystal of magnetite is surrounded first by a thin rim of sphene and then by a felspar zone. Crystals of apatite (A) and sphene (S) are distributed through the felspar zone which passes into normal amphibolite by the gradual appearance of hornblende (H) and biotite (B).

In thin section the rock is found to consist of hornblende and biotite in about equal proportions. The same clear felspar is present in the same proportion as in the normal members of the dyke series. Sphene is again abundant. The crystals are, perhaps, more numerous than in No. 928; but the average size is probably less than a quarter of that in No. 928. The magnetite blebs are surrounded by a very thin rim of sphene (fig. 7). Sometimes the blebs tail out a little in the direction of the schistosity. The felspar zone around the magnetite consists of a granulitic aggregate of clear felspar whose grain size is the same as the grain size in the normal part of the rock. The kind of felspar in the two portions of the rock is precisely the same. The felspar zone is marked more by the absence of the biotite and hornblende rather than by the felspar itself. Small crystals of sphene and apatite are present in the felspar zone. Apatite crystals and small pieces of felspar are also included in the magnetite. With the gradual increase in biotite and hornblende the felspar zone passes out into the normal biotite amphibolite.

In this example the rock is obviously part of the metamorphosed dyke series. It does not seem possible to account for the zonal structure on any primary igneous hypothesis. The magnetite crystals with a sphene rim are definite metamorphic products, and the clear felspar is also a product of the recrystallisation. There is, therefore, no reason to suppose that an association of these two products is anything else than a metamorphic structure. The formation of this structure in these circumstances involves a migration of certain material. It is, in fact, a small differentiation—magnetite centres have been enriched in magnetite and the biotite and the hornblende have been repelled from the felspar zone. The process of metamorphic differentiation in this case has involved the force of crystallisation.

The magnetite nucleus of sphene crystals is a normal feature in most examples of the amphibolite series at Cape Denison. The TiO_2 content of the primary ilmenite has combined with the felspar, producing sphene and hornblende, and it is, therefore, readily understood why the sphene surrounds the nucleus of magnetite or relic ilmenite. The relatively large crystals of magnetite with only a thin and often incomplete rim of sphene are abnormal in amphibolites Nos. 143, 637, and abnormal conditions must be pictured during their formation. It is certain that the TiO_2 content of these examples is not less than in the normal amphibolites, because they possess a high sphene content. The abnormal conditions have permitted certain magnetite crystals to enlarge themselves by attracting smaller magnetite crystals, and diffusion of magnetite, which is prevented in the normal case by a sphene shell, has occurred. We, therefore, suppose that the rate of diffusion of the magnetite molecules in these abnormal cases has been more rapid than the rate of reaction which produces the sphene. When the supply of magnetite molecules around any one centre has been nearly exhausted the sphene rim has become attached to the large crystal.

13.—Review and Discussion of Field Characters.

It is desirable to review the field characters in the light of the dyke origin of the bands. This metamorphosed series of dykes differs from a normal parallel system in the frequency and magnitude of the breaks in the surface outcrops. A normal dyke channel may here and there swell out into local bulges, but the general appearance of the bulges at Cape Denison, and the sharp, irregular way in which the bulge may terminate, seem to indicate that the bulges are not normal dyke swellings. In following the trend of the dyke we find no dyke in many places where we expect dyke, and, in other places, we find more dyke than we might reasonably expect. The field appearance suggests that the dyke walls have been squeezed together by a pressure of varying intensity at different points of the dyke plane. Where the pressure has been greatest the dyke wall might have closed together, and where the pressure has been least the dyke rock has formed a bulge. The normal width of a dyke is about 2ft., and the width of the enlarged outcrops is 9ft. or 12ft. At the same time we find the dykes running out of the thin parallel threads, and there are detached fragments of amphibolite adjacent to the dyke channel or along its continuation, which are wholly surrounded by the granodiorite gneiss. As far as observed, the foliation of the granodiorite gneiss bends around the contour of these isolated fragments. Sometimes they are precisely similar to the "canoe-shaped infolds" described in other areas.

There seems to be no reasonable alternative but to consider these "inclusions" as part of the dyke series. They have been shown to be so similar in character to the normal dyke, and so dissimilar from the granodiorite gneiss. In metamorphic areas, therefore, caution is necessary before we can assert the younger or the older age of the enclosing rocks. With our interpretation the "inclusion" is the younger rock—the reverse of the normal igneous or sedimentary deduction.

These abnormal dyke features demand an attempted explanation, especially as we will subsequently infer that analogous cases may exist in other areas of metamorphic rocks. One can, perhaps, imagine that branching offshoots of dyke into the adjacent gneiss might become detached from the main dyke channel during a period of excessive stress, and so form isolated fragments that lie adjacent and parallel to the main dykes. Such, however, provides no mental picture of the manner in which the main dyke has itself been rendered discontinuous.

Possibly there is an analogy with some curious features in the Ordovician rocks at Daylesford, Victoria, which have been recorded by T. S. Hart*. These Ordovician sediments are a steeply folded series, and unequal thickening and thinning of slate beds between sandstone beds is a common feature. The continuity of the slate beds is often broken. In a railway cutting near Daylesford slate now appears in numerous pockets of various shapes and sizes in a hard sandstone. At one place the pockets possess a prominent linear trend which would correspond in position and direction to a bed of slate. During the process of folding the slate has behaved towards the sandstone as a relatively plastic rock. The slate bed has had a thickness comparable in size with the minor irregularities and small displacements of the adjacent rigid sandstone, and been squeezed out irregularly so that it is now represented by a number of isolated fragments. The squeezing out of the slate goes so far sometimes as to show only occasional slate patches along a definite line of junction of two beds.

This, therefore, is the case of a primary band of solid rock that lost its identity by the play of stresses which have resulted in nothing beyond folded sediments. Could the disruption of the amphibolite dyke channels at Cape Denison occur in a like manner? Can the primary dolerite dyke, under the more intense conditions which have resulted in the decrystallisation, be considered a relatively plastic rock alongside the granodiorite?

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* "On some Features of the Ordovician Rocks at Daylesford," T. S. Hart, Proc. Roy. Soc. Vic., vol. XIV., N.S. pt. II., p. 167.

In this respect the only experimental data available are not encouraging. Adams and Coker* have carried out an investigation into the elastic constants of rocks during which they determined the cubic compressibility (D = ratio of the stress per unit area to the cubical strain) of five marbles and limestones, six granites and four basic plutonic rocks. The average of their results is—

	D (in inch, pound units).
Marbles and limestones	6,345,000
Granites	4,399,000
Basic intrusives	8,308,000

These results show that the granites are much more compressible than the marbles or the basic intrusives. The experimenters varied one set of readings over a temperature range of about 30° C. and found no perceptible difference. The actual case, however, under temperatures which are very high in comparison to living room temperatures, may be possibly very different.

These results are the reverse of what our proposed analogy would lead us to expect. Yet we have the fact before us that the impressed conditions were sufficient to cause the complete recrystallisation of the dolerite, but only a very imperfect recrystallisation of the granodiorite. In this sense the basic rock has been more susceptible to the superimposed conditions.

With these experimental data we must picture the basic dyke as a sheet of hard rock enclosed in a mass of relatively soft rock, viz., the granodiorite, and we must endeavour to understand what would happen to the system under the influence of great stress. If the hardness can be associated with brittleness, then, perhaps, we may picture the fracturing of the brittle sheet and the production of isolated fragments. That such fracturing actually occurs is shown by the observations of Adams and Barlow in the Haliburton and Bancroft areas. These authors figure and describe the initial stages in the disruption of an amphibolite dyke embedded in crystalline limestone†. The basic rock, on the experimental evidence, is less compressible than the limestone, and hence the experiments cannot furnish argumentative data against the disruption of a basic dyke channel in granodiorite.

We find further in the Kylesku to Loch Broom district, in the North-West Scottish Highlands,‡ that basic dykes have been observed to be wrenched into a series of isolated lenticles or phacoidal masses embedded in a zone of granulitic gneiss. We have, therefore, some reason to believe that the thin dyke channels of relatively hard rock have been rendered discontinuous and irregular in localised areas, in some manner not unlike that pictured in the case of a relatively thin band of soft shale embedded in sandstone at Daylesford. The present lenticular outline of most of the fragments can be ascribed wholly to recrystallisation under stress.

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* "An Investigation into the Elastic Constants of Rocks," F. D. Adams & E. G. Coker. Pub. 46, Carnegie Inst. Wash., June, 1906.

† "Geology of the Haliburton and Bancroft Areas," F. D. Adams & A. E. Barlow, Mem. 6, Can. Geol. Surv., 1910, fig. G, p. 160, Plates XXIX., XXX.

‡ "The Geological Structure of the North-West Highlands," Mem. Geol. Surv. Gt. Britain, 1907, p. 169.

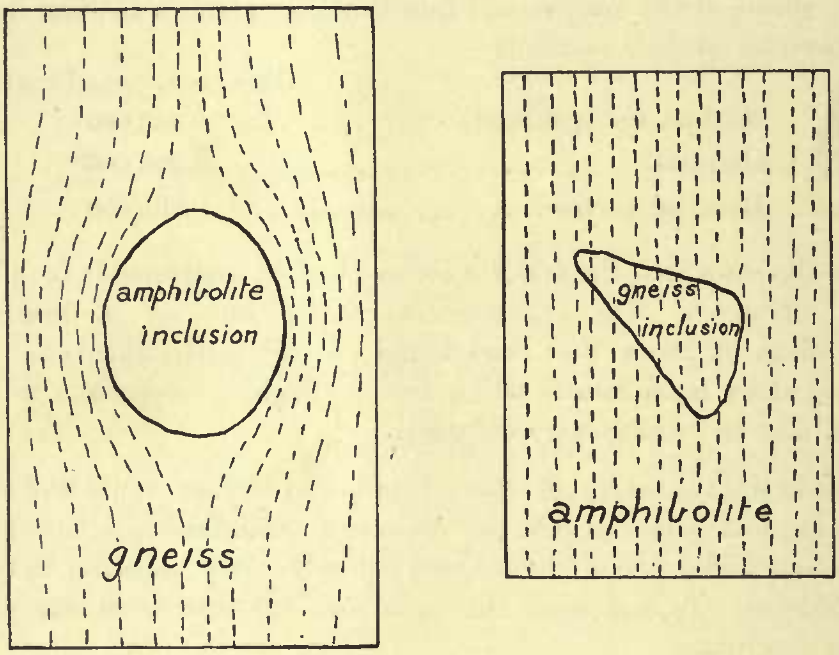

Fig. 8.

Diagrammatic Representation of the Manner in which the Foliation of the Granodiorite Gneiss Bends Around an Amphibolite Inclusion, and the Manner in which the Foliation of the Amphibolite Passes directly through a Quartz Felspar Gneiss Inclusion.

The manner in which the foliation of the granodiorite gneiss bends around the contour of the enclosed fragments of amphibolite is also a question inviting comment (fig. 8). The same kind of observation has been recorded by Cole, Adams, and others when it has been considered to demonstrate the stream lines of the gneissic flow around the inclusion which has been carried along like a log in a stream.* At Cape Denison the diverted foliation must be considered parallel with the foliation in the gneissic xenoliths embedded in amphibolite. In the latter the foliation of the amphibolite continues straight through the xenolith, sometimes quite irrespective of its angular outline. In the first case a block of amphibolite is embedded in a relatively large mass of granodiorite, and in the second a piece of granitic gneiss is embedded in a relatively large mass of amphibolite. The same general metamorphic conditions have been applied to each, and now the general foliation is diverted by the amphibolite block and not by the gneissic block. There is some disparity in size between the two typical cases, but we cannot see that any such disparity can provide adequate explanation.

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* Op. cit., p. 74.

It has been stated that the gneissic xenoliths seem to show a greater degree of recrystallisation than the granodiorite or aplite gneisses. This is probably to be explained by the degree of recrystallisation of the host. We obtain the following data from Van Hise * :—The change of augite to hornblende is exothermic, and, for an assumed average composition, the increase in volume is 4·30 per cent., provided all the resulting compounds are solid ; the change of augite to biotite is exothermic and, for an assumed average composition, the calculated increase in volume is 17·26 per cent. ; the change of felspar into each component of saussurite is exothermic and involves expansion of volume. Hence we can be quite certain that the recrystallisation of the dolerite which involves these changes has been accompanied by an expansion of volume and a liberation of heat. The recrystallisation of the granodiorite is not so complete as the recrystallisation of the dolerite. We may, then, imagine that the small gneissic xenolith enclosed in the relatively large mass of amphibolite has been exposed to greater pressure and higher temperature than the main mass of the granodiorite gneiss. As a result the small gneissic xenolith shows a different degree of recrystallisation than the granodiorite gneiss.

If a small mass of rock be enclosed within a larger mass of another type and the whole subjected to metamorphic conditions, then I think it would be generally expected that the foliation would travel independently through the two types as has happened in the case of the gneissic xenolith. We would, therefore, be inclined to view the diverted foliation as the abnormal case, even though it has been more commonly observed. As the general metamorphic conditions are the same in both cases, the only important difference lies in the greater expansion in volume of the amphibolite which is directly due to the chemical rearrangement. In this expansive effect we are forced to conclude must lie the cause of the diverted foliation.

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* "Treatise on Metamorphism," C. R. Van Hise, pp. 277, 278.

CHAPTER IV.

1.—THE GRANODIORITE GNEISS AT CAPE DENISON.

The chief rock type at Cape Denison is a coarse-grained, grey-coloured gneiss with a granitic appearance. It is foliated, and the strike of the foliation is N. 24$\frac{1}{2}$° W. The dip of the foliation is at a high angle, sometimes to the east and sometimes to the west. By observation of these dips the axes of folds seem to be determined, but no evidence of folding is forthcoming from the study of the black amphibolite bands that traverse the area parallel to the strike of the foliation. In the description of this gneissic type we exclude reference here to the patches of dark-coloured gneiss that may appear enclosed in the granitic gneiss.

In the hand specimen the grey gneiss has a varying amount of schistosity. Foliation is well marked in some specimens, while only faint in others. Beautiful examples of contorted gneiss are found in some places where the crystallisation schistosity is marked by bands of quartz and felspar (Plate XX., fig. 3). Yet the character of the gneiss is fairly constant across Cape Denison. Quartz, felspar, and biotite are always visible to the naked eye; magnetite is sometimes well developed, and there are patches where the same is true of pyrite. In some parts black vitreous allanite is obvious and developed in flat prismatic individuals. The largest allanite crystal obtained is an imperfect one, $\frac{7}{8}$in. long, $\frac{1}{4}$in. broad, and $\frac{3}{10}$in. thick. Apatite may also be abundant in the same areas as the allanite. Rarely large orthoclase crystals are found as white or reddish-white porphyroblasts up to 2in. in breadth.

In the hand specimens the normal texture of the rock is dominantly massive, but a tendency to the schistose types can always be detected. The biotite flakes may bend round large crystals of quartz and felspar, and then there is a tendency to augen gneiss and a rough lenticular texture. These lenticles may become flattened and more granular and then a distinct banded appearance is evident (Plate XI., fig. 5). Also the parallel bands of quartz and felspar against mica may develop the columnar appearance of wood gneiss (No. 143A).

The structure is granoblastic, due to the approximately isometric character of the quartz and felspar grains. Blasto-granitic structure is present, because the original big crystals of felspar and quartz in the granite can often be reconstructed in the cataclastic areas. Cataclastic structures are common when quartz and felspar crystals have been crushed. Mortar structure is common, but is usually best developed along the junction of two felspar crystals. Diablastic structure is frequently seen in the crush areas.

Specimen No. 11 has been selected and analysed as the normal type. It was collected from the site of the main hut at Cape Denison. No. 11 will, therefore, be described first, and then the other types can be dealt with in a relative manner.

The chief minerals present are quartz, microcline, orthoclase, andesine, perthite, and biotite. In smaller amounts are epidote, muscovite, sphene, chlorite, and calcite. As accessories are apatite, zircon, magnetite, pyrite, and hematite.

The quartz is present in irregular, indented grains, and frequently shows marked cataclasis. Some of the original crystals are replaced by interlocking granular aggregates with undulose extinction. Well marked strings of linear inclusions frequently pass through adjacent grains in such aggregates. Microcline, with its characteristic cross hatching, is abundant, and has developed from the original orthoclase of the granite. In some cases the transition from orthoclase is incomplete, and clear orthoclase forms the bulk of the crystal, which possesses a fringe with the cross twinning of microcline. The microcline exhibits some cataclasis. Perthite or networks of soda plagioclase and orthoclase are common in large individuals. The orthoclase is in large plates, and an albitic plagioclase appears in short, broken, more or less parallel strings which have the higher refractive index. This perthitic intergrowth can be found along lines of incipient fracture. Diablastic intergrowths of quartz and felspar, or of orthoclase and plagioclase, similar to the micropegmatitic intergrowths, are common. It is evident that the intergrowth has a metamorphic origin, because, not only are they most frequent in the crush areas, but they may be seen, with a rounded outline, developing parasitically within a plagioclase crystal. Sericite has developed from the orthoclase and is chiefly to be found in the crush areas. Like secondary biotite, it tends to wrap itself around primary quartz and felspar. In one case it appears as a zone between two microcline crystals. It may also appear as a rim on biotite crystals bending with the biotite. The original plagioclase has a refractive index above basal quartz and below other grains of quartz, and is, therefore, referred to as andesine. The application of Becke's bright line method is limited because the edges of the crystals are frequently crushed. Saussuritic aggregates have, in some cases, developed from the andesine, but only granular epidote and rounded blebs of secondary felspar can be distinguished in them.

Biotite is common in the crush areas but it is not confined to them, and some of it may have been preserved from the original granite. In some cases it tends to wrap itself around the relic quartz and felspar. Its colour is normally brown, but there is a subordinate quantity of green. Green chlorite in small amount is interlaminated with biotite. The biotite is often associated with epidote, sphene, and magnetite. Sometimes there is a thin rim of granular epidote around the biotite. The rim may also be sericite, which may develop into muscovite, because the latter is sometimes associated with the biotite. Muscovite is sparingly present in individuals comparable in size with the biotite. Pleochroic halos in biotite appear around inclusions of zircon and sphene. Epidote is present either in pleochroic crystals and grains or in the finely granular form. It is frequently associated with the biotite.

Sphene is usually granular, but some wedge-shaped crystals are seen. Sometimes it encloses a magnetite core, but not so frequently as in the amphibolites. Both sphene and epidote may be completely enclosed in biotite. Granular calcite has been found and has probably developed with the saussurite. Apatite, zircon, pyrite, and magnetite are scattered throughout. The apatite may be in large crystals, and the zircon is noticeable in small well-defined crystals with pointed ends which have clearly never left their primary host.

Other sections show variation in the degree of metamorphism of the rock. The crush areas may be less abundant and the andesine felspar better preserved. The twin lamellæ of the andesine may be curved and bent by the pressure. At the same time there may be less sericite, less perthite, and less of the diablastic structure. In other cases muscovite may be better developed, or chlorite may replace a portion of the biotite, while green hornblende may appear.

The microscopical examination, therefore, renders it apparent that this gneiss is the metamorphosed equivalent of a granite or a granodiorite.

CHEMICAL CHARACTERS.

The following analysis of the type specimen No. 11 was made in Victorian Geological Survey Laboratory :—

	I.	II.	III.	IV.
SiO_2	67·10	68·92	68·62	66·76
Al_2O_3	14·87	15·26	15·70	14·38
Fe_2O_3	1·14	0·80	1·66	2·04
FeO	3·76	3·30	1·77	3·75
MgO	1·80	1·64	1·28	2·71
CaO	3·47	3·04	3·56	4·62
Na_2O	2·56	2·71	5·08	1·44
K_2O	3·50	2·93	1·31	3·33
H_2O +	0·68	1·04	0·56	Ign. 0·49
H_2O —	0·11	0·22	0·10	—
CO_2	Nil	Nil	Tr.	—
TiO_2	0·68	0·70	0·26	—
P_2O_5	0·20	0·19	0·10	—
SO_3	Nil	—	—	—
Cl	0·05	Nil	Nil	—
MnO	Tr.	Tr.	0·07	0·14
NiO, CoO	Tr.	—	—	—
Cr_2O_3	—	—	Nil	—
CoO	Nil	—	—	—
Li_2O	Tr.	Tr.	—	—
BaO	—	—	0·02	—
S	—	—	0·03	—
Total	99·92	100·75	100·12	99·66
Specific Gravity	2·725	2·688	—	2·72

	I.		II.
Class	I.	..	I.
Order	4	..	4
Rang	3	..	3
Subrang	3	..	3
Magmatic Name	Amiatose		Amiatose

I. Granodiorite gneiss, Specimen No. 11, hut site, Cape Denison, Adelie Land. Analyst, J. C. Watson.

II. Granodiorite, near Old Sawmill, Hesket, Macedon District No. 35. Analyst, A. Hall.[*]

III. Typical banded gneiss, north side of Hopkin's Bay, Rainy Lake, Canada.[†]

IV. Biotite gneiss, near Sangobeag, Durness, Scotland.[‡]

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[*] "Annual Report of the Secretary of Mines, Victoria, for 1907," p. 61.

[†] "The Archæan Geology of Rainy Lake, Restudied," A. C. Lawson, Geol. Surv. Canada, Mem. 40, p. 93.

[‡] "The Geological Structure of the North-West Highlands of Scotland," Mem. Geol. Surv. Gt. Britain, 1907.

The analysis of the Cape Denison gneiss is strikingly similar to that of a granodiorite, and an analysis of a Macedon granodiorite is, therefore, inserted for illustration. The similarity is strong in all essential features, and both rocks occupy the same division in the American classification. Analyses of a banded biotite granite gneiss from the Rainy Lake region in Canada, and of a grey biotite gneiss from the Scottish highlands, are also quoted, and these show general similarities to the Cape Denison gneiss. Such comparisons, which could be readily multiplied, are interesting in emphasising the lithological uniformity in the Archæan terraines in all parts of the world. Similar rocks are known to exist in Australia and in South America and in South Africa.

The ratio of the potash to the soda is abnormal in the Canadian rock, while the alkali percentage of the Scottish rock is lower than that of the Antarctic rock. The differences in total alkali percentage are made important in Grubenmann's classification of schists. The group values and projection values of these three gneisses are :—

Rock.	Group Values.							Projection Values after Osann.		
	S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
No. 11, Cape Denison	74·0	5·1	4·0	7·8	—	0·5	1·6	6·0	4·8	9·2
Rainy Lake Gneiss	74·9	6·9	3·1	6·1	1·0	—	1·4	8·5	3·9	7·6
Banded Gneiss, Scotland......	72·3	3·7	5·3	9·5	—	0·2	1·7	4·0	5·8	10·2

THE CLASSIFICATORY POSITION.

The Cape Denison gneiss occupies a position on Osann's triangular projection (fig. 9), which is midway between the mean group values of Groups I. and III. The Canadian rock enters Group I. and the Scottish rock Group III. The Cape Denison gneiss should be considered as an intermediate type, and it occupies a position on the triangular projection halfway between the positions of these Canadian and Scottish rocks. Since, however, it is the metamorphic equivalent of a granodiorite, and since granodiorites are well known and definite rock types, it must be acknowledged that the metamorphic equivalents of granodiorites should be recognised. The Cape Denison gneiss is, therefore, best named as a granodiorite gneiss.

The mechanical effect of the metamorphism upon the original granodiorite is evident in the undulose extinction of the quartz, the cataclasis of the quartz and felspar, the prominent mortar structure, and the tendency of the colourless minerals to be arranged in layers of aggregated fragments. Evidence for the following transformations have also been noted :—

1. Partial decomposition of primary biotite into epidote, sphene, and ilmenite.
2. Partial decomposition of primary biotite into chlorite.

3. Partial saussuritisation of plagioclase.
4. Partial change of orthoclase into sericite.
5. Development of microcline from orthoclase.
6. Development of perthite from plagioclase.
7. Development of secondary biotite from chlorite.

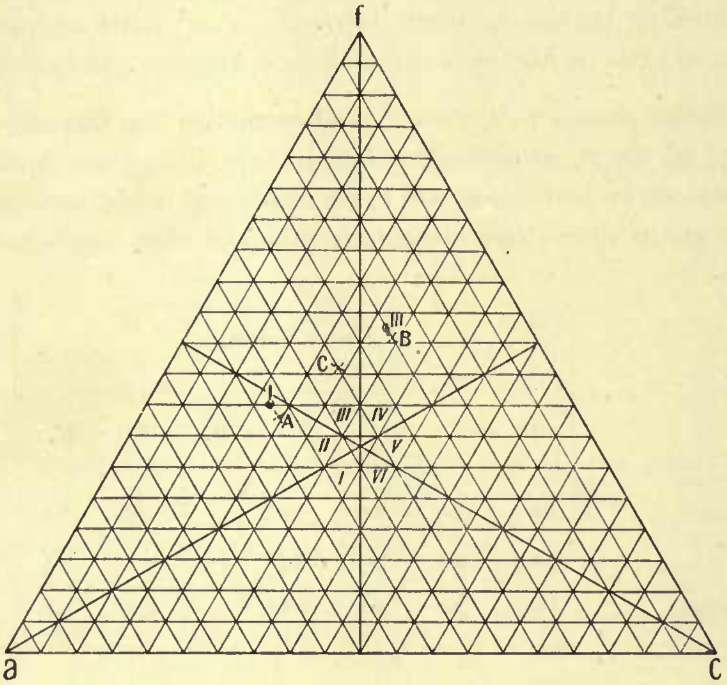

Fig. 9.

I. Mean position of Group I., the Alkali Felspar Gneisses.
III. Mean position of Group III., the Plagioclase Gneisses.
A. Rainy Lake Gneiss.
B. Scottish banded Gneiss.
C. Granodiorite Gneiss, Cape Denison.

The general survey of these changes indicates that the conditions of Grubenmann's epi zone of rock metamorphism have been dominant. The last three changes indicate that there is an approximation to the meso zone conditions, and so also does the occasional development of a rough crystallisation schistosity. Hence, while we consider that the rock may be referred to as an epi granodiorite gneiss, the meso zone tendency should be recognised.

2.—THE APLITE GNEISSES.

Associated with the granodiorite gneiss are quartz felspar gneisses which are the metamorphosed equivalents of pegmatite and aplite veins, which were most probably connected with the intrusion of the original granodiorite magma. These gneisses are red or white or grey, and appear as small bosses or veins in the granodiorite gneiss. The bosses may be a dozen yards or more in width and the foliation cuts through them independently of the outline of the boss or of the trend of the vein. As the surface outcrop of the rocks is perfectly fresh and uncovered, it could be observed in the field that the boundary between the aplite gneiss and the granodiorite gneiss was often indistinct, and there was frequently a gradual transition between the two. A set of specimens was accordingly collected across such a boundary and show a gradual change from the pure white aplite gneiss through pale grey shades to the darker grey granodiorite gneiss. In this we have another example of metamorphic diffusion. No field evidence is available concerning the relation of the aplite gneisses to the amphibolites. The small quartz veins that cut the amphibolites may be correlated with quartz veins which fill fractures in the granodiorite gneiss definitely subsequent to the development of the foliation.

No. 10A.—Specimen No. 10A is an example of the aplite gneiss and was collected from a vein about 18in. wide, close by the southern magnetic hut. The trend of the vein is approximately parallel to the direction of the foliation but was observed in section to cross it horizontally. In the hand specimen the rock has a pale-grey colour and a fine granulitic appearance. Quartz and felspar are the chief minerals, but small biotites are evenly distributed through the rock and produce perceptible schistosity. Occasional large crystals of allanite appear in the vein and have formed a centre of crystallisation around which felspar crystals radiate.

In thin section the rock is even grained with granoblastic structure and with abundant evidence of mashing and granulation. It is composed chiefly of interlocking crystals of quartz and felspar with smaller amounts of sericite, muscovite, and biotite, while magnetite, apatite, allanite, monazite appear as accessories.

The quartz appears in rounded, indented, and interlocking grains, and shows considerable cataclasis. Some of the granular aggregates of quartz have developed from the primary individuals of the pegmatite. At times there is a partial drawing out into lenticles and layers. Clear orthoclase is present, but the bulk of the potash felspar is microcline. Some of the microcline is quite clear and transparent and has developed from orthoclase as in the granodiorite gneiss. The microcline may appear as rounded blebs within the quartz crystal. Part may be relics of the original pegmatite because microcline is a common constituent of such, and some microcline crystals show strain polarisation and incipient granulitisation. Perthite is present. A small portion of the felspar has been sericitised and some of the sericite has passed over into muscovite.

Diablastic structure is common. That this vermicular interlocking of quartz and felspar is part of the metamorphic character is evident, because it is most common in the areas with marked cataclasis, and it appears wholly enclosed within felspar crystals. In other cases it has developed as a partial fringe to the plagioclase whose original outline is quite evident, or it may transgress as a bight into the side of a crystal. These features distinguish this intergrowth from the pegmatitic intergrowth of igneous rocks which is the crystallisation product of a eutectic mixture, and which is the last to crystallise in the consolidation of a rock magma. The diablastic structure does not have the character of a final product, but it has arisen contemporaneously with the other metamorphic minerals and structures.

Small crystals of ragged brown biotite are evenly distributed throughout the slide, and epidote may be associated with it. Odd grains of allanite are present, though no crystal comparable in size with the large examples exists in this slide. The development of allanite is, however, quite a feature of this locality. Macroscopically it has a black, pitchy lustre, and, in some cases, is surrounded by a reddish-brown zone. In thin section the allanite is found in reddish-brown pleochroic crystals. When associated with biotite it is surrounded by pleochroic haloes. They are biaxial with oblique extinction. The double refraction in many cases is high, and there may be a small amount of zoning. In such cases clinozoisite seems to be developed along its sides. In other cases it alters to a brownish-yellow amorphous gum-like mass. The allanite proved to have a refractive index greater than monobromnapthalin (1·648) and less than iodmethylene (1·740). When equal proportions of these two oils are mixed, part of the crystal had a refractive index greater than the mixture and part less. The mean refractive index is, therefore, in the neighbourhood of 1·68, a value which is on record for allanite. These characters are sufficient to render the identification fairly certain.

Since the cerium metals are present, and apatite is present as an accessory, it is to be expected that monazite should be found. Grains are found with a heavy dark border and with high polarisation colours and with marked similarity to zircons. Oblique extinction has been noticed, and these small crystals are, therefore, considered to be monazite. Pleochroic haloes around monazite in biotite are strong. Accessory grains of magnetite and reddish hematite are fairly common, while clear apatite is less so.

The rock corresponds closely to the family of Glimmerarme meso alkali felspar gneisses in Group I. of Grubenmann's classification. The development of microcline and perthite and the diablastic structure rather signifies the meso zone characteristics. It may, therefore, be described as an alkali felspar gneiss, poor in mica, or an aplite gneiss developed from an aplite vein under conditions approximating to those of the meso zone.

No. 150.—An example (No. 150) from the pegmatite bosses is very similar in most respects to the example (No. 10A) collected from a vein. It shows variation in its larger grain size, and its more massive texture, and in general, it shows stronger epi zone features. Microcline and perthite individuals are present, but there is a greater amount of sericite. Relic plagioclase lamellæ can be recognised in large sericitic masses. The development of sericite can be found along shear planes in microcline crystals. There is also some kaolinisation of the orthoclase. Fracturing and granulation of the quartz and felspar is more prominent than in the preceding example, and so also is mortar structure. The diablastic structure is not common and mostly in incipient stages. The mica content is small and includes green chlorite, green biotite, and white muscovite. The chlorite and biotite are often associated in one individual. Grains of epidote are associated with the mica. A little calcite is present, and magnetite, apatite, monazite, and allanite are again accessories. The epi zone characters are here considered dominant, and the example is described as an epi alkali felspar gneiss, poor in mica, or as an epi-aplite gneiss.

In further examples the amount of sericite may increase sufficiently to yield sericite gneiss. Occasionally a relic garnet is found with considerable development of green chloritic products along the cracks. The percentage of ferromagnesian minerals increases towards the margin of the bosses as we pass outward through metamorphic diffusion types into the granodiorite gneiss.

3.—INTERPRETATION OF CERTAIN VARIATIONS IN THE GRANODIORITE GNEISS.

Since the boundaries of the aplitic masses with the granodiorite are in places destroyed and replaced by metamorphic diffusion types, there is no a priori reason why such diffusion types should not, under favourable circumstances, extend across the whole width of the vein. In such contingencies the vein will completely lose its identity and become part of the main gneissic mass. A study of metamorphic diffusion specimens indicates that this has actually taken place. Rocks which were collected in the field as varieties of the granodiorite gneiss are now considered to be diffusion types. This is particularly the case with gneisses collected from the locality by the magnetograph house, which is the precise locality from which the conception of metamorphic diffusion is developed in the case of the amphibolites.

In this case the gneiss has a lighter colour, due to the absorption of some quartzo-felspathic material. The composition and the granularity are variable and the texture is usually more massive. A feature of the locality is the abundance of monazite and allanite (Plate XI., fig. 6). The allanite is found in exactly the same manner as noted in the aplitic gneiss, *i.e.*, frequently with a radial arrangement of felspar around it. No definite gneissic vein is recorded from the precise point where the examples were collected, and they are very similar to the metamorphic diffusion products on other parts of Cape Denison.

Specimen No. 60 is an example of the pale grey gneiss of this type. The chief constituents are quartz, orthoclase, perthite, and microcline. The ferromagnesian constituents form less than 4 per cent. of the slide, whereas the normal ferromagnesian percentage of the granodiorite gneiss is about 18 per cent. Its silicity would, therefore, be probably more comparable with the aplite gneiss than with the granodiorite gneiss. Diablastic interlacings are abundant. Chlorite and epidote are associated with biotite and muscovite. No hornblende is present. Apatite, monazite, and allanite are accessories, and of these allanite is the best developed.

Specimen No. 154 is a similar example, but possesses coarser grain size. There is also a larger ferromagnesian percentage than in the previous case, and the biotite appears in clusters. The irregular distribution of biotite is noticeable in the hand specimen. Muscovite is again present. Large crystals of quartz, orthoclase, and plagioclase are the dominating minerals. Some microcline is present, and the orthoclase does not show much sericitisation. The plagioclase seems to be albite oligoclase or an albite, and is, therefore, the plagioclase of an aplitic vein rather than the plagioclase of the granodiorite gneiss. Apatite is the most abnormal constituent and forms large crystals which, though not uniformly distributed, contribute 3½ per cent. of the slide. Monazite is also an abundant accessory, so that the P_2O_5 content of this sample must be unusually high. Allanite is very well developed and zircon also seems to be present.

The resemblances to the aplitic gneisses are apparent. This likeness can only be reconciled with the field evidence by the recognition of metamorphic diffusion and its obliteration of the individuality of the vein.

CHAPTER V.

CORRELATION AND CRITICISM OF ANALOGOUS AREAS.

1.—General.

Crystalline schists have now been reported from widely separated parts of the Antarctic continent. Large areas of metamorphic rocks can, therefore, be assumed to exist under the ice sheet. They have already been regarded as forming the ancient platform on which the central part of South Victoria Land was built.* The present knowledge of the distribution of these rocks indicates that they form the platform of the Great Antarctic Plateau.

In the Ross Sea region the known extent of the gneisses has been extended by Shackleton's expedition and by Scott's last expedition. They have been proved to exist in King Edward VII. Land on the east. They are now known to range on the west to Adelie Land and to Queen Mary Land. Dredgings from the "Challenger" expedition indicate that they probably extend still further west, and they have been recorded from West Antarctica.

Streaks of hornblende schist are found associated with the gneisses in the Kukri Hills, in South Victoria Land, by Ferrar. Amphibolites and pyroxene granulites have been recorded from the moraines by the Shackleton expedition.† Amphibolites and hornblende schists have also been mentioned in the description of the rocks obtained by the "Belgica."‡

In Antarctica, as elsewhere, amphibolites are found in manifold forms wherever the crystalline schists appear over a considerable area. Large areas of crystalline schists appear in every continent, and any attempt to correlate occurrences immediately becomes a tabulation of areas of Archæan rocks, and this is unnecessary here. As a consequence of the lithological similarity of most Archæan terraines it follows that any theory correctly deduced from one area should immediately find wide application. The interpretation of one area should materially assist the interpretation in all other areas. That this has not been the case has been in some measure responsible for the more or less disorganised condition of the study of metamorphic areas, and for the complexity that is commonly associated with their study. More particularly, conflicting opinion has been responsible for Cole's description of amphibolites as puzzling rocks.§

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* Natural History, vol. I., Geology, H. T. Ferrar, Nat. Ant. Exped., Brit. Mus., p. 25.

† Geol. vol. II., Brit. Ant. Exp., Mawson, Walkom.

‡ "Resultats du Voyage du S. Y. 'Belgica.'" Expedition Antarctique, Belge, Géologie II., Teil, Dragomir Sistek, 1912.

§ "Rocks and their Origin," G. A. J. Cole, p. 148.

If any theory can replace opposition by harmony such a theory will grow in strength as each new concordance is produced from the field of geological literature. The theories of metamorphic differentiation and metamorphic diffusion which appear to account for certain features at Cape Denison seem to be applicable in other areas. In some cases they produce interpretations quite different from the published explanations, and the value of these interpretations depends partly on the assurance that can be given to the Cape Denison phenomena and partly on the value that can be attached to Grubenmann's great work, " Die Krystallinen Schiefer." In many cases it has seemed to us that the description of the products of metamorphic diffuson and metamorphic differentiation are better than those which have been presented from Cape Denison. The Cape Denison descriptions have necessarily suffered from our inability to revisit the area. The field work could not be revised with the progress of the work in the laboratory, and the conclusions cannot be forced home with the wealth of evidence that might otherwise have been available.

We propose now to examine the data from some of the other areas from the standpoint that the Cape Denison study has created. Attention is only given to a few recent and important publications, and the criticism is offered to stimulate interest and to direct attention to explanations which have not been hitherto considered.

2.—North-West Highlands of Scotland.

Features at Cape Denison and Cape Gray are reflected in the areas of Lewisian gneiss in the North-West Highlands of Scotland. The Lewisian gneiss (p. 41)* has been subdivided into—

1. Fundamental Complex.
2. Ultra basic dykes.
3. Basic dykes of dolerite, epidiorite (amphibolite), hornblende schist.
4. A few dykes of exceptional composition.
5. Granites and pegmatites.

Groups 2 and 3 have been found to be associated with the Lewisian gneiss, and yet intrusive into the Fundamental Complex, and are so referred to the pre-Torridonian. Teall remarks (p. 39) that in many places the dyke-like character is obvious, as more or less vertical walls of black rock clearly cut across the gneissic banding. But, in other places, owing to movements after or during the injection of the dykes, the dyke-like character is lost and the rocks of the dykes become more or less incorporated with the earlier complex.

Horne remarks (p. 36), in connection with the basic intrusions, that it is of special importance to note that in the southern tracts, where the dykes are represented by hornblende schists, which seem to become part of the Fundamental Complex, and where intrusive junctions are only occasionally met with, biotite gneisses and hornblende gneisses are characteristically developed. Hence the obvious nature of the dyke masses at Cape Gray, their less obvious appearance at Cape Denison, and their partial destruction at Cape Denison, are matched by similar instances in the Scottish area. Remarkable variation in mineral and structural composition is noted in both areas, and the dominant types are the same in both cases.

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* The pages quoted in connection with this area have reference to the following publication :—" The Geological Structure of the North-West Highlands of Scotland," B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. W. Hinxman, J. J. H. Teall. Memoirs Geol. Surv. Gt. Britain, 1907.

The above remark of Horne illustrates the incomplete separation of the second and third groups from the Fundamental Complex, and it also appears to be evidence of the development of biotite gneisses and hornblende gneisses in the same way as at Cape Denison, viz., by the destruction of the walls of the basic dykes by metamorphic diffusion.

In some cases, as in the Gruinard district (p. 176), it is clearly shown that the basic dykes form an absolutely different series to that which supplied the early basic material in the Fundamental Complex. On the other hand, in the description of the Cape Wrath to Laxford area (p. 107), it is recorded that the grey biotite gneiss, the hornblende biotite gneiss, and the dark gneiss alternate in bands and areas of varying breadth, having no sharply defined boundaries, but graduating from the more acid to the more basic types. These types cannot be distinguished on the field map, and are therefore considered only as portions of the primary mass. In the description of the Loch Maree to Gairloch area (p. 195) it is recorded that field distinction is impossible between the hornblende gneisses with quartz and hornblende gneisses without quartz on account of their variation. These last two cases afford further analogy to the Cape Denison rocks, where hornblende gneisses are considered to be metamorphic products of a mixture of grey gneiss and amphibolite, resulting from metamorphic diffusion.

Thus it is a perfectly natural result that it should be recorded in the Loch Maree and Gairloch district (p. 195) that the "early basic rocks" (those which have not been separated from the Fundamental Complex) are more variable in composition than the basic dykes. The basic dykes, which happen to be parallel to the direction of foliation, are only recognised as such when they have escaped metamorphic diffusion, and a varying amount of diffusion will produce varying results. In the Loch Carron to Point Sleat (Skye) district the rocks are stated (p. 262) to consist of biotite and hornblende gneisses with bands of hornblende schist, which are considered to represent the basic dykes in the unmodified areas of Lewisian gneiss in Ross and Sutherland. Had these bands been dislocated, and had they then suffered metamorphic diffusion, they would certainly present the same features as the "early basic rocks." I do not argue that there is but one series of pre-Torridonian basic dykes in the North-West Highlands to which both the so-called "early basic" and the "basic" rocks may be referred. There are at least two, and possibly more, but I do mean that the "early basic" rocks may possibly represent the torn-up and diffused remnants of some dyke series, and that they are not to be looked upon as necessarily earlier, without further consideration, than the enclosing gneiss.

In the Loch Laxford to Kylesku area it is stated (p. 134) that gneisses enclose frequent lenticles and lumps composed entirely of hornblende and pyroxene. Again, a leading feature of the Fundamental Complex in the Gruinard district (p. 177) is the extraordinary abundance of knots of basic material in the gneiss. A beautiful, unfoliated diorite is here recorded, but the most abundant consist of the dark hornblendic rock. The same type of thing is observed in other places, and they are looked upon as products of segregation, in common with the acid gneiss, from an intermediate magma, or as included fragments of an older rock system. Now in the Kylesku to Loch Broom area (p. 169) it is found that near areas of dominant stress a dyke may be wrenched into a series of isolated lenticles or " phacoidal masses." The evidence of the Scottish area, apart from the Cape Denison observations, thus shows that a dyke can be torn into fragments which may now appear as isolated inclusions. Hence a complete account of the Scottish Highlands must consider the possibility that many of the hornblende and pyroxenic clots may be the metamorphosed remains of torn-up fragments of basic dykes. They may be stated to be differentiation products caught up in the manner illustrated at Depot Island, South Victoria Land*, by the intrusion of granite, which have been subsequently modified by metamorphic processes; but there is no positive proof, at present, that requires them to be looked upon as " earlier " than the enclosing gneiss.

Equally evident as the metamorphic diffusion in the North-West Scottish Highlands is metamorphic differentiation. Rocks are recorded by Teall (p. 45) which consist of pure hornblende, and which are found as knots, lenticles, and bands. Similar separation of the biotite is mentioned in the description of the Loch Maree and Gairloch district (p. 193). Some of these are no doubt similar to the hornblende and biotite patches which have been considered as metamorphic differentiation products at Cape Denison.

In discussing hornblendites and pyroxenites (p. 45) Teall finds that, by the gradual increase in the amount of hornblende, the pyroxenites pass into hornblendites. They form banded masses, and the possibility must arise as to whether both these types are not metamorphic differentiation types. With suitable metamorphic conditions pyroxene could very well differentiate itself with equivalent result to the hornblende. The recorded section (p. 47), where four hornblendite bands and four pyroxenite bands occur in 4ft. 5in., could well be an example of metamorphic differentiation developed with alternating conditions. It may, indeed, be viewed as a magnified crystallisation schistosity. Where Teall describes the rocks containing hornblende and pyroxene (Group III.B2) he finds that such are related to the pyroxene gneisses. He states (p. 63) that it is impossible to avoid the conclusion that they have been formed from the pyroxene gneisses by secondary metamorphic processes. It is interesting to note that this type of change of pyroxene to hornblende is just that which Grubenmann would describe in transition from the kata zone conditions to the meso zone conditions.

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* "Geology." vol. I.. Brit. Ant. Exp., Plate LXXXI., p. 246.

The phenomena illustrated on Plates VI., XII., XIV., XVIII. of this British Memoir are exactly paralleled in the Cape Denison area. Plate VI. would there be described as a stage in the metamorphic differentiation of the constituents of a primary basic rock. In Plate XII. the hornblende differentiation is more advanced, and an imperfect banded arrangement appears. Plate XIV. may have originated where a basic dyke has run out into parallel threads, or it may be again metamorphic differentiation. A dyke fragment with smaller pieces detached from it, together with a certain amount of migration, might give rise to an appearance similar to that on Plate XVIII.

After the publication of the preceding memoir in 1907 the Geological Survey of Great Britain has produced a series of memoirs dealing with the North-West Highlands. These memoirs provide the explanation of the published quarter sheets, but, like the 1907 memoir, are largely a mass of field data that await the co-ordinating process of some worker.

In the "Geology of the Seaboard of Mid Argyll" (Memoir No. 36, 1909) I have noted an interesting (p. 6) description of phacoids of epidiorite in pebbly limestone matrix. These phacoids are recognised as fragments torn off epidiorite dykes during crushing, and the limestone is considered to have played the part of a plastic matrix. This is another illustration of what may happen to a dyke sheet submitted to strong stress.

In the geology of Glenelg, Lochalsh, and south-east part of Skye (Memoir No. 71, 1910), there is an excellent illustration (Plate V.) of a large knot of foliated basic rock in the Lewisian gneiss at Rudha Caol. The general appearance of this knot could be matched among the disrupted dykes at Cape Denison. At Rudha Caol the basic inclusions have varying composition, indicating metamorphic diffusion or metamorphic differentiation, or both. Another illustration (Plate VIII.) of the same memoir provides a good example of metamorphic differentiation where a basic lenticle is illustrated in thinly-banded hornblendic gneiss.

In the geology of the Fannich Mountains and the country around Loch Maree and Strath Bromm (Memoir No. 92, 1913), we have again reference to the exposures which have been illustrated in the large 1907 Memoir, and which we have considered to provide examples of metamorphic diffusion and metamorphic differentiation. The explanations given in 1907 are adhered to, and Plate VI. is still the picture of a magma of intermediate composition from which the more distinctly basic and acid rocks are in the process of formation. Another view is stated which regards the bulk of the rock as a mixture rock formed by the mingling, probably while in a semi-fluid state, of basic and acid portions. This latter view is a step nearer to the recognition of metamorphic diffusion phenomena. There is also recognition (p. 23) of transitions by insensible gradations from ultra basic rocks to basic rocks. On Plate III. of this memoir there is an illustration of garnetiferous muscovite biotite gneiss with lenticles of "pegmatite." It can be pointed out that these lenticles may be fragments of broken pegmatite veins, but they are quite possibly metamorphic differentiation products, as the same quartzo-felspathic material is distributed right through the base of the gneiss.

If, then, the phenomena of metamorphic diffusion and metamorphic differentiation be upheld, and the rock types be traced back with their aid to the primary types, we must surely arrive much nearer the true history of the Fundamental Complex in the Highlands. If the Complex be studied from the view point of these theories it seems possible that some of the apparent complexity will disappear. The rocks must no longer be approached through the eyes of a mineralogical classification, as attempted by Teall, which obscures relationships and separates similar rocks. True metamorphic types must be recognised, and the kata zone, meso zone, and epi zone varieties of the same type must be correlated together according to Grubenmann's method or to some analogous system. Metamorphic diffusion types and metamorphic differentiation types should also occupy divisions in the mental field of view before it would be possible to present an orderly exposition.

3.—Haliburton and Bancroft Areas, Canada.

Amphibolites are recognised as forming an important part of the Canadian Archæan rocks, and considerable study has been given to them by Adams and Barlow in the Haliburton and Bancroft areas in the Province of Ontario. Their work is embodied in a memoir published by the Geological Survey of Canada in 1910*. Papers containing their results appeared earlier in the Quarterly Journal of the Geological Society of London† and in the Journal of Geology‡. In presenting criticism on that portion of their work which pertains to amphibolites, attention is only given to the memoir, the latest and most complete publication.

From a study of this memoir we find that it appears to be claimed that amphibolites are formed in diverse ways throughout the area. According to these different modes of origin the amphibolites may be classified in the following manner :—

1. Those derived by alteration of basic dykes or similar igneous intrusions—
    - (*a*) Those which can now be recognised as true dykes.
    - (*b*) Those which appear as bands in crystalline dolomite, &c.
2. Those derived by alteration of limestones by action of intrusive granitic magma—
    - (*a*) Those which appear in a linear manner along the contact of the limestone masses and the gneiss.
    - (*b*) Those which appear as inclusions in the grey gneiss.

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* "Geology of the Haliburton and Bancroft Areas," F. D. Adams & A. E. Barlow, Geol. Surv. Can. Mem., No. 6.

† "The Laurentian System in Eastern Canada," F. D. Adams. Q.J.G.S. 1908, p. 127.

‡ "On the Origin of the Amphibolites of the Laurentian Area of Canada," Journ. Geol., 1909, vol. 17, p. 1.

3. Those derived by the metamorphism of impure bands in the limestone series—
   - (*a*) Those which are described as "pyroxene hornblende gneiss" or "pyroxene hornblende granulite."
   - (*b*) Those which are described as "feather amphibolite."
   - (*c*) Those which contain orthorhombic amphibole.

The amphibolites of igneous dyke origin are recognised when they are found in the field to cut across the bedded white crystalline limestone. Adams and Barlow find that the field evidence is essential to recognise the igneous origin with certainty, but other cases which are macroscopically identical with the established dykes, and which appear interbanded with crystalline dolomite or crystalline limestone, are also considered to be probably igneous. A chemical analysis is quoted, and it is stated (p. 161) that it is highly probable that they were diabases. It is interesting to note that this altered Canadian diabase and the typical amphibolite (No. 629) from Cape Denison are so strikingly similar that they occupy the same division of the American classification.

Adams and Barlow have assured themselves that amphibolites are formed by the second method by a study of the contact phenomena in the border zones of the granite gneiss. Where the granite has intruded limestone the changes produced are divided into two classes (p. 87)—

1. Alteration of the limestone into masses of scapolite-bearing pyroxene rock.
2. Alteration into pyroxene gneiss or amphibolite.

The No. 1 change is proved by finding all possible transitions between the pure limestone and the pyroxenite, which is stated to occur (p. 88) at or near the contact with the granite. With simple contact metamorphism we expect to find in a traverse across the boundary transition from limestone to pyroxenite and then a sudden change from pyroxenite to granite. This seems to be indicated, and the varying nature of the product in a measure supports the theory; but it needs to be demonstrated that the same metamorphism which affected the granite *after* its consolidation would not produce the observed results in the limestone. The contact alteration is considered to be of the pneumatolytic type, but it is difficult to understand how such would produce the biotite rock (p. 93) or the felspar scapolite rock (p. 94). It is stated that the field relations of these two rocks to the limestone in Harcourt and Dudley (p. 96) render it almost certain that they are produced by the alteration of the limestone.

The second change is found (p. 97) "where granitic magma shatters the invaded rocks and floats away the fragments in its moving mass." It may be pointed out that not only is such an idea opposed to the present day conceptions of the manner in which holocrystalline rocks of coarse granularity arise, but it only permits heat as the metamorphic agent. These inclusions are stated to be similar to those which are described in the granite gneiss at great distance from the junction with the limestone. It is stated (p. 98) that the field evidence is scarcely susceptible of any interpretation other than that, under the influence of granitic intrusion, the limestone has, in the zone of most intense action, been altered into an amphibolite. The limestone is found to gradually pass into the amphibolite by the development in it of certain silicates.

A series of thin sections from a suite of specimens of the amphibolites are examined (p. 103), which are claimed to illustrate the transitional stages of alteration. A significant fact was noticed which was found difficult of explanation on the accepted hypothesis. At one end of the series is a rock containing augite, calcite, and felspar, and at the other end is a rock containing dominant hornblende with plagioclase and subordinate augite. It was found that no passage existed between the characteristic pyroxene of the recrystallised limestone and the characteristic hornblende. The hornblende and pyroxene found together in the one section are fresh and show no alteration of one to the other. The absence of transition is important, and shows that the rocks dealt with are metamorphosed products in which both the augite and the hornblende are primary metamorphic minerals, not secondary one to the other. In metamorphic rocks of basic origin hornblende is frequently derived from the alteration of augite, and in such cases the evidences of direct transition are abundant in thin section. The occurrence is, in fact, highly suggestive of the phenomena of metamorphic diffusion. The so-called gradual alteration may very well be a series of metamorphic diffusion products between the limestone and the amphibolite. Were this same type of argument accepted it could be shown at Cape Denison that amphibolites are the product of alteration of granite. Metamorphic diffusion products naturally show the chemical transition (p. 104), and will also yield an explanation of the microphotographs on Plates XIV., XV., XVI. of the memoir. The chemical analyses are useful to show again the constant features of amphibolites. No. 1*b* (104) again falls into the same division of the American classification as the typical amphibolite (No. 629) of the Cape Denison rocks.

With the outlook of metamorphic diffusion one finds no evidence to disprove the theory that along the junction of granite and limestone there has been a later intrusion of basic rock, either in the form of a dyke or a boss. During the subsequent metamorphism of the area the limestone and the basic rock have recrystallised and the granite changed to gneiss. The enclosed fragments of basic rock in the gneiss might well be considered as the torn-up fragments of a possible dyke. The transition of basic rock to limestone is possible under the conditions which give rise to metamorphic diffusion, and the isolation of blocks of an intrusive rock in the intruded rock is believed to be an established possibility.

If a dyke mass has appeared along the limestone-granite boundary, it is not surprising that (p. 97) among the many inclusions of amphibolite a careful search should only lead to the discovery of one single fragment of coarsely crystalline limestone. Thick bands of hornblende schist, which are looked upon as originally intrusive rocks, similarly appear at the sides of, or within, outcrops of altered sedimentary rock* in

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* British Geological Survey Memoir, 1907, op. cit., p. 238.

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the Loch Maree and Gairloch district in the Scottish Highlands. The theory of an amphibolite intrusion is quite consistent with the general statement (p. 115) that it is almost a universal rule that the limestone near the contact is filled with various silicates which have been developed in it, while the inclusions actually present in the granite near the contact are composed of amphibolite or some allied rock.

The unrecognised presence of metamorphic diffusion is upheld by Adam's and Barlow's discussion (p. 115) of the question "Has the granite gneiss anywhere actually dissolved the invaded rock ?" Several instances are quoted to show that the granite magma has been rendered basic by absorption of amphibolite. The peculiarities of the gneiss are those which have been received long after consolidation, and the effects of solution by the primary magma can only be interpreted with the greatest care. In this case the gneiss is conceived as a molten magma and the conceptions of flowing gneiss and the confusion of bedding and foliation are dangerously wrong and court erroneous interpretation. It is stated (p. 117) that where the granite runs into a corner between two tongues of amphibolite a basic development of the granite is seen also, due, in all probability, to a partial solution of the invaded amphibolite ; that the products of solution bear (p. 122) a marked resemblance to the grey gneiss. This "solution" may readily be another case of that process which has been called metamorphic diffusion.

It is interesting to note (p. 114) that in one area of gneissic granite, that in the township of Methuen, southern portion of the Kasshabog Lake, amphibolite inclusions are abundant and appear in a linear belt parallel to the foliation. Again (p. 118) the limestone, as shown on the Bancroft sheet, has a number of belts of amphibolite parallel to the strike. This recognition of linear development is suggestive of dyke origin.

With regard to the amphibolites (Group 2*b*) which appear as inclusions in the grey gneiss, Adams and Barlow state (p. 121) that they are portions of rock forming the walls or roof of the batholith which had fallen into the granite magma and had partaken of its subsequent movements. He also adds that there is positive proof that this is the correct and only explanation in several parts of the area. The positive proof, however, is not convincing. Even if there were no reason to believe, as affirmed by Adams and Barlow (p. 122), from the form or composition that they are ever due to magmatic segregation, there will remain the hypothesis of a broken and disrupted dyke. I fail to see even how the form, much less its composition, can preclude the hypothesis of metamorphosed primary magmatic segregation products. We find on page 160, fig G, an illustrative sketch in the memoir actually showing an amphibolite in the first stages of disruption, and on page 76, fig. A, we see the characteristic lens shape similar to that of fragments which have been proved to be part of dykes. Again, fig. B, page 76, we see again the disruption of the amphibolite inclusions. We therefore see that the Canadian evidence is sufficient, apart from the evidence from Cape Denison or the Scottish Highlands, to show that a detached fragment of amphibolite, enclosed by gneiss, is not necessarily to be regarded as earlier than the invading granite in the metamorphic areas. This fact lends considerable support to the theory that many of the Canadian amphibolites are portions of intrusive igneous rocks, frequently in the form of dykes. It is very interesting, therefore, to read the footnote (p. 121) which states that B. Frosterous, in his work in Finland, finds that the amphibolites which are characteristic associates of the granite gneiss of Southern Finland are probably for the most part altered dyke rocks. How far the dyke theory is applicable in Canada cannot be at present determined.

There remains the third class of amphibolite which are considered to be derived from the metamorphism of impure bands in the limestone series. The cause of the metamorphism is assumed to be (p. 164) "undoubtedly the granite lying below and exerting its action upward." The evidence relied upon is the interbanded character (p. 165) of thin amphibolite bands in crystalline limestone on the Hastings Road on lots 31 and 57, near the village of Ormsby. To the north of this the limestone bands disappear and the amphibolite covers a great area. This evidence could be adequately interpreted by the supposition of a primary intrusive mass which sends out tongues into the surrounding limestone. Hence it is difficult to see how the evidence can carry the burden of proof placed upon it by Adams and Barlow.

The "feather amphibolite," for which a sedimentary origin is claimed, seems to be a different type of rock from the above amphibolites which the authors have called the granular amphibolites. It is questionable whether the "feather amphibolite" is a typical amphibolite. No analysis is given of the rock, so that it is impossible to strictly correlate it with the normal amphibolites and to see whether it, like them, falls into Grubenmann's group of amphibolites. The hand specimen (Plate XXXVII.) shows striking differences, and to group the rock types illustrated in the memoir by microphotographs (Plates IV., XXXVIII.) under the one generic term "amphibolite" without modification is scarcely justified. The mode of occurrence, too, is different, because the "feather amphibolite" is not found (p. 62) as inclusions in the granite gneiss. The scientific term "amphibolite" will have much decreased value if made to include dissimilar things.

The amphibolite containing orthorhombic amphibole, which is described as a product of the extreme alteration of limestone by a granitic magma, is also an abnormal type and grouped among the amphibolites without a consideration of its chemical composition. It contains abundant gedrite and garnet associated with cordierite, quartz, biotite, iron ore, rutile, and sillimanite. No felspar is present, and the rock could be better described as a cordierite-bearing garnet gedrite schist. Though it is not stated whether the rock is schistose or massive, the microphotograph (Plate XXXIX.) shows a schistose character. Anthophyllite has been found in dyke rocks in the Lewisian gneiss*, but this mineral composition suggests a chemical composition quite unlike an igneous rock. No actual evidence of the nature of the origin of this rock is stated, but its composition could be expected to be that which would result by the recrystallisation of an impure magnesian limestone.

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*British Geological Survey Memoir, 1907, op. cit., p. 49.

In another part of the memoir we have noticed a description (p. 127) of the nodular granite of Pine Lake, township of Cardiff. The granite is metamorphic, and shows in part curious nodules which average 2in. to 3in. in diameter. The nodules are composed chiefly of quartz, muscovite, and sillimanite. Muscovite and sillimanite are especially metamorphic minerals, and it is therefore likely that the nodules are formed under metamorphic conditions. The chemical composition of the nodules is decidedly not that of an igneous rock, and yet they occur in granite! It seems, therefore, feasible to appeal to metamorphic differentiation. The nodules have been described as sometimes aggregating and forming foliated veins, and in this case the whole vein must be looked upon as a metamorphic differentiate. The instance is in some respects analogous to the courts of crystallisation that have been described in No. 143 from Cape Denison, but in the Canadian instance the product is coarser and more readily recognised as metamorphic.

Summary.

Summing up, it seems that the positive statements by Adams and Barlow in the memoir, and by Adams in his published summaries, concerning the origin of amphibolites, are not sufficient. It cannot be considered as proved that normal amphibolites can be formed by the alteration and recrystallisation of impure calcareous sediments. The evidence that has been presented in detail can be shown to be explicable on the supposition that the amphibolites are recrystallised basic intrusive rocks. It is suggested that unrecognised examples of metamorphic diffusion have been interpreted as proof of the change of limestone to amphibolite. The amphibolite inclusions in the gneiss have not been shown not to be the alteration of primary basic differentiation magma products or the isolated fragments of fractured and disrupted basic igneous dykes. The authors have stated (p. 62) that it is a remarkable fact that the amphibolites originating in the two very diverse manners often resemble one another so closely that it is impossible to tell them apart. Such resemblance is to be expected on our alternative hypothesis of igneous intrusion.

4.—Highlands of New Jersey.

The results of the Cape Denison observations are also applicable to the phenomena described by Fenner in the Highlands of New Jersey*. Fenner describes hornblendic bands which may show (p. 598) remarkable continuity and parallelism and which may pinch out for a distance, recontinue after an interval, and appear as knots or inclusions. There is no mashing or granulation. There is frequently a sharp contact between the "inclusions" and granite, although an interlocking of crystals may occur. Fenner states (p. 601) that it appears in some cases that the basic minerals at the immediate contact have become involved in the granitic magma without losing their parallelism, so that a perfect transition is produced from the hornblende or biotite gneiss with prominent foliation, through types in which, with increasing proportion of granite, no parallelism of structure can be preserved. The direction of the bands is parallel to the schistosity of the granite gneiss, which may be schistose as well as massive. In places (p. 602) the dark minerals appear to have been taken up or digested by the magma and to have crystallised out again in large blades.

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* "Mode of Formation of Certain Gneisses in the Highlands of New Jersey," C. N. Fenner, Journ. Geol., vol. XXII., pp. 594-612, 694-702. Under this head numbers in brackets refer to this publication.

Here, again, we find the interpretation of phenomena among gneisses coloured by the conception that everything happened when the granite was molten. The gneissic characteristics have been impressed after the consolidation of the granite by the influence of stress. The processes which result in crystalline schists are entirely distinct from those which result in normal igneous rocks. Solution, as we know it in igneous magmas and liquids, is inapplicable to bodies which are to all intents and purposes solid. The so-called " basic " minerals which are found exhibiting parallelism are metamorphic minerals which have arisen in response to the impressed external conditions which have caused the gneissic characters. The gradual transition, observed by Fenner, is simply significant of metamorphic diffusion, and it is obvious in the field because the two rocks in contact have strong difference in colour. In perfect accord with the theory of metamorphic diffusion, he states (p. 604) that where there is the largest amount of dark basic rock the adjacent granite contains the greatest quantity of dark silicates, and where the inclusions are rare the granite is very light coloured and nearly free from ferromagnesian minerals. From this observation he rightly concludes that the dark minerals in the massive granite are derived from the basic rock. The term " granite " is persistently used throughout the paper, but it is questionable how far it is correct to do so, for the normal rock of the series seems to be a granitoid gneiss. But Fenner is impressed with the conception that the granite is intrusive into the rocks of basic composition with laminated structure after the manner of lit-par-lit injection. He has tried to examine the process by which a thinly fluid granitic magma could be injected between the layers of an original sedimentary rock. In doing so he finds difficulty in understanding how these thin walls of original rock could remain intact during injection and, at the same time, allow transfusion of material.

Like many other workers Fenner has placed considerable value on the evidence of the so-called inclusions and the transfusion. As has been pointed out in other cases, " inclusions " in metamorphic areas do not necessarily signify an earlier age than the enclosing primary granite. It does signify an age earlier than the development of the metamorphic characters, but not earlier than the granite magma. There is nothing in the evidence presented to show that these dark hornblende bands and " inclusions " are not the metamorphosed product of thin basic dykes which, in the first place, intruded the granite, and which, in the subsequent metamorphism, have had their boundaries partially destroyed by metamorphic diffusion, and which have been fractured and broken so that fragments can now appear detached and isolated as if they were inclusions caught up by an invading magma. New mineral formations have resulted from the stress, and the mashing and granulitisation of the primary constituents are absent. In this manner, then, the rocks of the Highlands of the Hudson in North-Western New Jersey can be correlated with occurrences at Cape Denison and in other parts of the world.

The Assimilation Theory.

The assimilation theory for the production of hornblende schist, biotite and hornblende gneisses, which has been illustrated in the preceding paper by Fenner, has had wide application. It has been recently emphasised by Cole, who has quoted a large number of references, and who considers that the undermining and weakening of the earth's crust by molten magma is the only interpretation of the widespread phenomena.* Cole states:—" Again and again strongly banded gneisses occur in which granitic material alternates with sheets of hornblendic or biotitic schist. The biotitic varieties can often be traced back into amphibolites. In places lumps of these amphibolites are seen, streaked out at their margins, and providing a clear explanation of the dark bands throughout the gneiss. This swallowing up of a mantle of basic material by a very different and highly siliceous magma rising from below is seen to be a world-wide feature, wherever we find the lower crust-layers brought up within reach of observation." Further on he continues:—" We see the highly metamorphosed material further attacked by the great cauldrons under it and becoming seamed with intersected veins. Block after block has been caught, as it were, in the act of foundering into the depths. In the gradual absorption of these blocks, and their penetration by insidious streaks of granite, we see pictured on a few square yards of surface the destruction of a continental floor." Such is the catastrophic manner in which the metamorphic phenomena are accounted for by assimilationists. It needs to be pointed out that as soon as any of the features are demonstrated to be the result of metamorphic action as opposed to igneous action, the theory is rudely shaken. If another explanation, *e.g.*, metamorphic diffusion, be found for the supposed gradual assimilation, a modified statement becomes necessary. If, further, some of the supposed invaded crust be actually shown to be younger in age than the granitic magma, the theory must completely crumble unless recast. The widespread nature of the evidence is no more than the widespread occurrence of lithologically uniform areas of the crystalline schists. We must include Cape Denison among such areas of crystalline schists, and there we find no reason to appeal to molten magmas for explanation of the observed phenomena.

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* Cole, Pres. Add. Sect. C., B.A.A.S. Manchester, 1915.

5.—Geology of the Lizard and Meneage. Flett and Hill.*

This memoir contains an account of the metamorphic region of the Southern Lizard surveyed and described by Dr. Flett. In this area an extraordinary number of rock types are developed which have been the object of study of a large number of workers. The earlier work has been summarised by Flett and incorporated in his own work, so that a very full and clear description of the rocks and the rock problems is presented. One, however, turns to the memoir to discover if any recognition has been made of true metamorphic types, and the general impression obtained from the memoir is that the rock problems have been treated rather from the standpoint of igneous rocks and of rock magmas. It appears that the metamorphic character of the rock is considered to be of subsidiary importance in comparison with its primary nature, and the value of some of his conclusions is thereby lessened.

The serpentine, one finds, is looked upon as a modified igneous rock. It is continually referred to as the intrusive body, and there is only occasional reference to the peridotite from which it is derived. The serpentine in all cases is considered (p. 80) as a weathered or decomposition product of olivine. This is the recognised origin of serpentine in many cases, and for this reason Grubenmann says† that the position of serpentine among the crystalline schists, from which normal weather products are excluded, is doubtful and uncertain. Nevertheless, Grubenmann considers that certain occurrences must be included therein, and, therefore, creates the serpentine family in his classification of the crystalline schists. It seems to us that Flett has produced strong evidence for the similar inclusion of the Lizard serpentine.

We cannot agree with Flett that there is any reason (p. 97) to think that the main serpentinisation of the Lizard peridotites took place at a comparatively late period of their history, though there may be some development of serpentine in subsequent weathering, as there is even in the example of primary serpentine recorded by Weinschenck‡, and referred to by Flett (p. 97). Subsequent veins of chrysotile which are unaffected by the schistosity seem to me to have very little bearing on the matter. At Cape Denison there are numerous quartz segregation veins, independent of the foliation, which may contain large and beautiful crystals of epidote, while epidote may also appear along any joint plane of the gneisses and schists. These formations of epidote are clearly subsequent to the development of foliation, yet no one would assume from this that the formation of epidote in the amphibolite and schists was subsequent to the development of foliation. In fact the epidote in some schists takes definite part in the foliation, and has been proved to be a definite part of the mineral composition of the amphibolite series.

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* "Memoirs of the Geological Survey. England and Wales." Sheet 359, 1912. The numbers placed in brackets in the following have reference to pages in this memoir unless a special reference is given.

† Op. cit., vol. II., p. 113.

‡ "Spezielle Gesteinskunde," 2nd edit., 1907. p. 184.

It is recorded (p. 20) that there are certain zones or belts in the serpentine which have a rudely concentric arrangement. This zoned character is stated (p. 21) to be "clear evidence that the serpentine is an intrusive stock that welled up and forced outwards the surrounding schists." In this it seems that the very metamorphic imprint of the mass is turned into evidence of intrusion. The metamorphic character of the Lizard serpentine is more or less affirmed by Flett when he says (p. 70) that the microscopic examination shows that very few specimens can be described as normal igneous rocks; that the normal poikilitic association of olivine and pyroxene is absent except for traces in the least modified bastite serpentine or "weathered lherzolite"; that the large pyroxene crystals are commonly broken or have their cleavage planes twisted; that tremolite is found to increase in quantity hand in hand with the development of foliation and augen structure. As tremolite is a well-known metamorphic mineral, the zone of tremolite serpentine may very well be but one phase of the metamorphic product due to varying metamorphic conditions. The augen structure, the foliation, and the schistose character that is described (p. 69) is strong evidence of the metamorphic, not weathered, character of the rock. The absence of foliation and schistosity in some parts of the serpentine body is no evidence to the contrary, as massive textures are common among the crystalline schists. Further, the serpentine has been demonstrated by Flett (p. 120) to be earlier in age[*] than the group of rocks styled "Kennack Gneisses," which bear the very marked individuality of typical crystalline schists. These schist characters have been impressed by certain external metamorphosing conditions, and it is not reasonable to suppose that the peridotite, surrounded now by metamorphic rocks, has escaped the whole of these forces. If, then, the serpentine be acknowledged to be a primary metamorphic product in any occurrence at all, it is reasonable to concede that the Lizard serpentine is likewise a metamorphic product, and should therefore be treated primarily as such. If the water content of serpentine is considered a barrier to the hypothesis, it must be remembered that Grubenmann postulates considerable water in his epi zone of metamorphism in which hydrous minerals like chlorite are common.

Throughout the memoir there are frequent references to fluxion banding in the serpentine in the so-called gabbros, and in the Kennack gneisses. Now, fluxion structures are true igneous structures developed by movement in the magma during consolidation. If they appear in metamorphic rocks they can only do so as relic structures, and if the decrystallisation during metamorphism is intense, fluxion structure will be very difficult to recognise. It therefore becomes incumbent to examine the evidence put forward in order to discover if a different aspect will create a different interpretation. Before doing so, however, we will more fully explain the standpoint from which the question is approached.

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[*] In a later publication, "The Crystalline Rocks of the Lizard," issued as a pamphlet by Bowes and Bowes, Cambridge, Prof. Bonney does not accept this opinion of Flett's and insists on his own former interpretation, viz., that the Kennack gneisses are *older* than the serpentine. Whether Bonney be correct or not, the argument remains unaffected, as far as the Survey memoir is concerned.

Though Becke has explained in 1892 that dynamo-metamorphism may involve either complete recrystallisation, resembling contact metamorphism, or granulation, there arose a tendency in the following years to associate only mechanical structures with pressure effects. This tendency produced Weinschenck's attack on the use of the term "dynamo-metamorphism" which is declared to be vague, and to connote the personal interpretation of the user. Weinschenck's attack is directed mainly against the idea of purely mechanical transformation of rocks. Grubenmann* has approved of this criticism, but he opposes the introduction by Weinschenck of the terms "piezo-crystallisation" and "piezo-contact-metamorphism." "Piezo-crystallisation" is the crystallisation which proceeds in a magma under the influence of a tangential thrust and produces primary pressure banding. "Piezo-contact-metamorphism" is the influence exerted by the intrusive magma and its attendant gases or vapours on the enveloping rocks during "piezo-crystallisation." The ideas are introduced by Weinschenck to explain the large area of metamorphic schists surrounding the central massif of the European Alps. Grubenmann maintains that these terms are unnecessary, as the kind of metamorphism is explained as soon as the fundamental physico-chemical factors are defined. The special terms are superfluous provided we consider collectively the temperature, the uniform pressure, the stress (non-uniform pressure), and the factor of the individual substance at the time of the metamorphism. In this Grubenmann is dealing with rocks which undergo no essential change in composition during metamorphism. Metasomatic changes and all rocks whose composition is changed by igneous exhalations and heated waters are not considered. Johnston and Niggli† have reached the same conclusion in their exposition of the general principles underlying metamorphic processes.

Grubenmann, Van Hise, and others have attempted to classify these conditions of temperature, etc., by reference to zones of metamorphism when each zone is characterised by special conditions which grade into the special conditions of the neighbouring zone. Crook has adversely criticised the value of the conception of metamorphic zones as given by Van Hise, partly because the crustal zones fail to provide a basis of genetic classification of rocks either in a general or metamorphic sense, and partly because he believes in the "paramount importance of igneous intrusions as agents of metamorphism"‡. Provided, however, that the zones are made sufficiently definite, and are not made dependent on depth within the earth's crust, they are very useful in defining the sets of conditions under which changes occur.

Rock flowage is a term that frequently appears in portions of the literature on metamorphic geology, but no use is made of it in our discussion. It is, no doubt, a useful term in structural geology, when, for structural considerations, the earth's crust is divided into a zone of fracture and a zone of rock flowage. Deformation of the rocks occurs in the former by fracturing, and in the latter by rock flowage involving a permanent change of form without conspicuous fracture. This permanent change is supposed to be accomplished by interior readjustments of rock substances by chemical, mineral, and mechanical changes, and produces the slaty cleavage and schistose structures. The latter are included by Leith under the one term " flow cleavage "*.

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* "Die Kristallinen Schiefer," vol. I., p. 46.

† "The General Principles underlying Metamorphic Processes," Johnston and Niggli, Journ. Geol., vol. XXI., p. 63.

‡ "The Genetic Classification of Rocks and Ore Deposits," T. Crook. Min. Mag., vol. XVII., July, 1914, p. 55.

We find, however, that there are objections to the use of these terms in a treatment of metamorphic rocks. It is desirable to analyse and distinguish more carefully the interior readjustments which are combined in rock flowage. We need to distinguish between slaty cleavage and crystalline schistosity, which are separated by the degree of the all-important recrystallisation, while all the physico-chemical conditions of recrystallisation are not included in the zone of rock flowage. A zone of rock flowage implies a zone where there is a dominating stress combined with a hydrostatic pressure, and it will not include a zone of very high hydrostatic pressure with less important stress; and under such conditions we picture certain recrystallisations. As a general term " rock flowage " includes too little and as a restricted term too much.

Primary gneissic banding or primary pressure banding has been frequently recorded on the margins of igneous masses. They are terms which are frequently supposed to involve movement in the rock magma. We consider, however, that the primary pressure banding, apart from injection banding, can be considered as a metamorphic texture without any appeal to fluxion or moving magma, and that it is identical with the schistose structure produced by recrystallisation under stress. The coarse granularity and holo-crystalline character of even-grained plutonic rocks indicate that there has been no movement in the magma during its consolidation. Large crystals do not grow uniformly in moving solutions, and it is difficult to see how the symmetrical arrangement of the mineral constituents in a schistose margin can be produced by movement in a viscous, semi-solid rock. For the injection of rock magma against the weight of the overburden of enveloping rocks we must postulate big orogenic forces. If these forces continue after the magma has been brought to rest they are distributed through the magma only as a hydrostatic or uniform pressure. Cooling and consolidation proceed under the uniform pressure as in any normal case. Though the crystallisation may be uniform throughout the whole mass, we imagine that the outer margin will become solid before the centre. If, after the development of this solid crust, the pressure causing intrusion be still maintained in the molten portion, the hydrostatic pressure in the molten portion will be exerted normally on all parts of this crust, which is then affected as if subjected to a stress (non-uniform pressure) or a squeeze (fig. 10). This stress, combined with the other factors of temperature, etc., produce, not movement, but the stable molecular rearrangement and the gneissic banding in the manner most recently expounded by Grubenmann†, Johnston, and Niggli‡, and proved experimentally by Wright§. This stress may also possibly be produced by the expansion caused by the crystallisation of the central portion. When the pressure is relieved the crystallisation proceeds normally and the centre becomes massive. Non-uniform pressure is essential to produce the gneissic banding, and it cannot be applied to a liquid. Therefore, not until the magma has become frozen and solid can the gneissic character be impressed upon it. We find no satisfaction in Van Hise's statement* that "the parallel orientation of minerals in the original gneisses formed from magmas is due to differential stress during the primary crystallisation of the rocks."

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* " Structural Geology," C. K. Leith, Constable & Co., 1914, p. 76.

† Op. cit., vol. I., p. 42.

‡ Op. cit., p. 610.

§ " Schistosity by Crystallisation," F. E. Wright, Amer. Journ. Sci., vol. 22, p. 224.

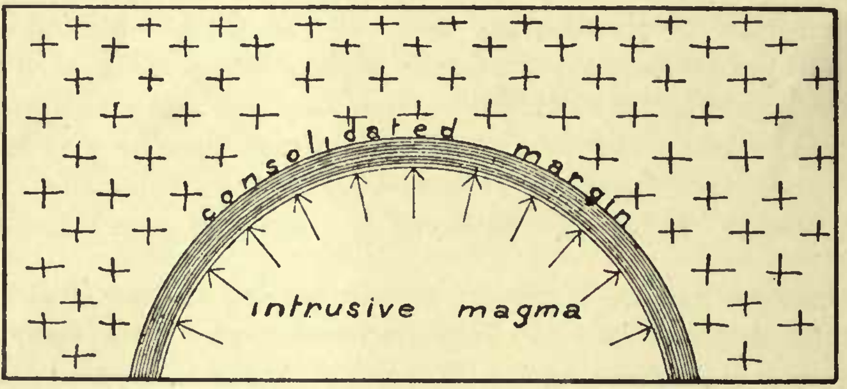

Fig. 10.

Diagram Showing the Formation of a Schistose Margin Without any Appeal to Movement in the Magma. Hydrostatic Pressure in the Magma is Exerted Against the Marginal Rim as Normal Stresses, which Induce Recrystallisation and Schistosity.

In Wright's experiments he aimed at producing crystallisation, and with it schistosity, from solution under strain. He does it by heating a solid, viz., glass, under strain. He looks upon glass as an undercooled liquid, but it can equally well be named a solid solution, as glasses fall within Van Hoff's definition of a solid solution. He really shows that crystallisation within a solid, not crystallisation in a liquid under strain, produces the schistosity. The difference between the liquid and the solid becomes, of course, a fine point when viscous substances are being considered, though the difficulty could be arbitrarily settled by looking upon a viscous mass as solid as soon as it can take a stress. It cannot be inferred from his experiment that schistosity can be produced in the first crystallisation of a cooling magma.

From these considerations it is necessary to strongly oppose the use of the terms "flowing gneiss" and "fluxion gneiss" which constantly appear in geological literature dealing with metamorphic rocks. To be consistent it is also necessary to oppose the introduction of the term "injection foliation," proposed by Flett, because it likewise carries false meaning. A term "injecting banding" may be appropriate for the banding which Geikie† considers is produced by the injection of aplitic magma into dark schists with biotite and hornblende. Banding of a similar nature is found at Cape Denison, where thin threads of basic magma intruded the granodiorite and have partially maintained their integrity during the metamorphism. Such banding is an igneous structure which the metamorphism has not effaced, and is analagous to a lit-par-lit injection on a small scale. Both fluxion banding and foliation are insisted upon by Flett in the Lizard serpentine, in the gabbros, in the Kennack gneisses, and in the granite gneiss. But there does not seem to be any great difference between the two except a mineralogical one. The fluxion banding (p. 22) is marked by olivine and pyroxene, and the foliation by serpentine, and it is stated that they are parallel to one another and are so intimately connected that they seem to be parts of one phenomenon and must be closely allied in origin. We also notice that the figure referred to both on page 22 and page 68 as an illustration of fluxion banding is titled " The foliation banding in the serpentine." When we consider the Lizard serpentine to be a metamorphic rock belonging to the epi zone of metamorphism, it is probable that the so-called fluxion banding and foliation are part of one phenomenon.

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* "Treatise on Metamorphism," C. R. Van Hise, p. 782.

† "Text Book of Geology," A. Geikie, p. 256.

" Injection foliation " is the conception which Flett puts forward to account for the remarkable foliation of the system of gabbros dykes that penetrate the serpentine. He states (p. 94) that the foliation of the dykes is in nearly all cases parallel to the margin of the dykes, whatever be its course ; that it is equally well marked in the horizontal, vertical, and inclined dykes, and when one foliated dyke cuts another each has its own direction of foliation ; that consequently the schistosity at once suggests fluxion movement ; that where a dyke bends the schistosity bends with it, and if a dyke forks, each branch is foliated parallel to its length. It is therefore supposed (p. 23) that " the dyke rock was forced upwards in a plastic state under severe pressures, and the foliation was produced as the injection went on, being really an injection foliation." If this is so, the mineral constituents are arranged parallel to the direction of pressure instead of at right angles to it. Further, if non-uniform pressure is an essential factor in the production of gneissic structures, then it is not right to connect the foliation of these Lizard dykes with their infilling with liquid magma. Not till the dyke matter has become solid can the non-uniform pressure affect it, and we can only avoid the difficulty by permitting the plastic magma to have the properties of both a liquid and a solid. This seems to us unreasonable, and we therefore think that the super-induced foliation must find some explanation independent of any movement along the dyke channels. The heat of the primary magma may be a contributing factor, but its supposition is unnecessary, as other sources of heat can be found. Rejecting, therefore, the theory of injection foliation, we tender the following for consideration.

We have explained that there is good reason to think that the Lizard serpentine has been developed from a peridotite by metamorphic processes. The development of serpentine by meteoric waters, if present, is only subsidiary. The serpentine has been forced to develop during geological time under the physico-chemical conditions in the depths of the earth crust that exist in Grubenmann's epi zone of metamorphism or in Van Hise's zone of katamorphism. External energy has been impressed upon the system, and olivine and pyroxene have passed over into serpentine, liberating a large quantity of heat and molecular energy. The accompanying figures, quoted from Van Hise's tables,* show that this type of alteration in peridotites is accompanied by the formation of minerals of lower specific gravity and larger molecular volume.

	Specific Gravity.	Molecular Volume.
Olivine	3·4	50·40
Enstatite	3·2	31·22
Augite	3·4	63·38
Bastite	2·6	118·11
Tremolite	3·0	138·44
Serpentine	2·57	107·2

According to Van Hise's interpretations of the reactions, the following figures express the increase in volume of the individual systems :—

Mineral Change.	Heat Change.	Volume Increase Per Cent.
Serpentine from enstatite..	+ K	14·25 or 38·26, according as all compounds do or do not separate as solids
Serpentine from diopside ..	+ K	56·32 or 0·44, according as all compounds do or do not separate as solids
Bastite from enstatite	+ K	22·77 or 46·87, according as all compounds do or do not separate as solids
Tremolite from diopside ..	+ K	5·68 or 10·15, according as all compounds do or do not separate as solids
Serpentine from olivine ...	+ K	29·26 or 15·19, according as all compounds do or do not separate as solids 37·13 or 12·43, according to composition of olivine
Tremolite from olivine	− K	12·29 volume decrease

In all cases except the last, which Flett has only stated as a possibility in the Lizard serpentine, there is increase in volume and liberation of heat. Hence, in a large mass of rock like the Lizard serpentine, there will be enormous expanding forces exerted on the enveloping rocks and on any dyke sheets that happen to traverse the serpentine. These forces will act as compressive stresses approximately normal to the dyke plane whatever may happen to be its direction. The serpentinisation thus causes the squeezing of the dyke rock. Large quantities of heat are liberated at the same time, and the compression is met by the molecular rearrangement of the constituents with the development of those forms and shapes which are most stable against the imposed conditions. As a necessary consequence gneissic banding appears parallel to the trend of the dyke. The metamorphic character of the so-called gabbro dykes is therefore caused in the first place by the same external metamorphic forces which are producing serpentinisation, and in the second place by the simultaneous internal metamorphic forces that develop during serpentinisation. Irregularity is, therefore, to be expected, and it becomes easy to understand why it should be commonly observed (p. 98) that the gabbro dykes are wrenched off by irregular planes of movement. The general theory would cause the impression recorded by Flett (p. 98) that these veins have been caught up in powerful but irregular movement; that they have been softer and more plastic than the peridotite which surrounded them and have yielded to stresses; that there has been an internal shearing which has crushed the minerals and set up a rough foliation. It also yields explanation why there should sometimes be a development of foliation (p. 96) in the serpentine walls parallel to a dyke junction. This foliation in the serpentine is always parallel to the foliation in the dyke, is very similar to it in character, and in some cases becomes gradually lost as one passes outward from the edge of the dyke.

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* "Treatise on Metamorphism," p. 195.

Apart from external pressure the expansion of the peridotite will be more or less symmetrical in all directions from the centre of the mass, and so there will arise approximately hydrostatic pressure in the centre and non-uniform pressure towards the margins. Such will be more or less the case, but the external pressure will tend to destroy the symmetry and move the region of hydrostatic pressure away from the centre. There will therefore arise concentric zones of similar pressure throughout the mass. Where the hydrostatic pressure prevails there can arise the coarsely crystalline massive product, and where non-uniform pressure dominates there can arise the schistose character. Consequently there may arise the approximately zonal arrangement of tremolite serpentine around the bastite serpentine as noted by Flett (p. 20). The dunite serpentine may be the result of a marginal facies in the primary peridotite. It has a lower alumina and lime content than either the tremolite or bastite serpentine. The microscope shows that it consists entirely of olivine and its alteration products. As an absorption of heat is required for the formation of tremolite from olivine, we have only to suppose that the heat factor was not sufficiently strong on the margin to yield a tremolite schist, and serpentine without tremolite would be found. If, then, we are to give the Lizard serpentine a metamorphic history of this kind, we cannot accept Flett's statement (p. 68) that fluxion banding in the Lizard serpentine is a very common phenomenon until the metamorphic processes have been fully considered and the laminæ which are marked by olivine, or by olivine and pyroxene, or by olivine and tremolite, have been shown not to be comparable with Grubenmann's crystallisation schistosity texture. It would be very remarkable if fluxion banding is always parallel to the subsequently induced foliation which, in turn, is parallel both to banding and foliation of the adjacent hornblende schists and to the actual line of junction of the serpentine and the hornblende schists. Apart from fluxion banding this parallelism is a necessary consequence of the suggested explanation.

It is very interesting to note that Flett finds (p. 74) that there is a transition between, or an intermixture of, the serpentine and the adjacent hornblende schist at the junction at Pol Cornick; that there is little evidence of crushing to be found in the slides cut from the junction; that there is a little development of tremolite, and the minerals are exceptionally fresh. It seems reasonable to infer that a primary metamorphic product has arisen at this point as the result of metamorphic diffusion, with the destruction of the hornblende schist-serpentine boundary. This means that the hornblende schist and serpentine have suffered together similar metamorphic processes, and hence we have further justification in treating the serpentine mass as a metamorphic product rather than as a weathered peridotite.

We may now, perhaps, go further and make reference to the inter-banding of schist and serpentine described (p. 75) as due to folding. Canoe-shaped infolds of fine, rotten hornblende schist are mentioned. These remind us of the lenticular inclusions of the amphibolite dykes in the granodiorite gneiss that have been torn off the main dyke channels at Cape Denison during the metamorphism of the area. Such "infolds" have been referred to as "inclusions" by Adams and Barlow in the Haliburton and Bancroft area in Canada, and considered to be evidence of the lesser age of the enclosing rocks.* As we have found that this is not necessarily the case, we must apply great caution in the interpretation of the folding in metamorphic areas until the field phenomena are better understood. More especially as it is observed by Flett (p. 99) that no part of the gabbro has been folded, and all the movement seems to have taken the form of internal shearing in a large unwieldy mass which would not fold.

Flett distinguishes two series of hornblende schists in the Lizard, and both are determined as metamorphosed igneous rocks. One series is spoken of as the Landewednack schists (p. 46) and the other the Traboe schists (p. 50). The Landewednack schists are considered to be older than the Man of War gneisses, and the Traboe schists are younger, though Flett acknowledges their inter-relation is difficult to make out. Apart from differences in weathering, the Traboe schists are distinguished from the Landewednack schists (p. 51) by the following characters:—

1. Paucity of epidote.
2. Its relation by folding and transition to the serpentine, for no case is known where the Traboe schists occur at any considerable distance from the margin of the serpentine.

Now the presence or absence of epidote in an hornblende schist depends upon the temperature factor in the metamorphism. Epidote will only form if the temperature is not too high to drive the water out of the molecule. The inference is that the Traboe schists have been metamorphosed at a higher temperature than the Landewednack schists—a fact which has no bearing on relative age. If we neglect the doubtful evidence of folding there only remains the fact of transition which, it is maintained, can be interpreted as an example of metamorphic diffusion. With this explanation it is to be expected that the Traboe type of schist should only be found near the margin of the serpentine whose metamorphism has been shown to develop additional heat. Hence, on the present available evidence the Traboe and the Landewednack schists can only be looked upon as slightly different facies of the same primary rock. There is at present no valid reason for discrimination in age. Further, the possibility that the Traboe schists represent an igneous rock intrusive into the serpentine has not been disproved.

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* "Geology of the Haliburton and Bancroft Areas, Ont.," Adams and Barlow. Mem. No. 6 Can. Geol. Surv., p. 62.

Accompanying the Landewednack schists (p. 50) are streaks and nodules of epidosite, and it is very interesting to note that Flett looks upon these as due to some kind of segregation during metamorphism. They are similar to the Cape Denison epidosite, which we have called a metamorphic differentiation product. Epidosites also occur abundantly (p. 36) among the green schists and granulites of the old Lizard Head series. Here Flett considers them as facies of the other rocks rather than types entitled to recognition as a distinct group, and states that some of them are segregations, nodules, and vein-like masses in the hornblende schists produced either by weathering before shearing, or by chemical segregation during movement; that others are probably due to weathering of a fine type of hornblende schist and hornblende granulite; that others are quartzose granulites in which epidote may represent volcanic detritus or ashes, or may be a secondary infiltration during metamorphism. It seems to me that such an aspect is only possible when metamorphic rocks are denied their own special individuality, because epidosites do not fit into any sedimentary or igneous rock group. In this case again the epidosites can be explained as metamorphic differentiation products.

The gabbro dykes (p. 81, *et seq.*), whose foliation we have contended is in no way connected with their injection, occur only in the serpentine. In addition to the dykes there are intrusive bosses, the largest of which is the Crousa Downs Gabbro. These gabbros were grouped by Teall into—

1. Gabbro Schists.
2. Flaser Gabbro.
3. Normal Types.

Flett also considers them in this manner. The treatment from the standpoint of igneous rocks is evident here in the nomenclature. Though the dykes are known to be metamorphic, the igneous rock term "gabbro" is applied. The gabbro schists are coarse-grained saussuritic hornblende schists which are a well-known type developed from dolerite or diabase. The present coarse-grained character is not necessarily evidence of the original coarse granularity of the gabbro. The flaser gabbro, which is the prevailing type, is also a metamorphic rock, because it includes all those gabbros which exhibit distinct evidence of crushing and recrystallisation. The normal gabbros are restricted to the neighbourhood of Coverack, and as one recognises the general metamorphism of the Lizard, and also as a weak "fluxion banding" is mentioned, one must question the term "normal gabbro" for the least altered members of the series. In the description of the normal gabbro it is stated that the felspar contains cracks due to incipient fracture and crushing, as well as cloudy spots of saussurite; that the augite appears as diallage and brown hornblende is often associated with diallage; that the olivine "weathers" to serpentine and magnetite, and sometimes to dense aggregates of talc; that hypersthene is rare and only seen as thin borders to clusters of olivine; that there are reaction rims of diallage or hypersthene around the olivine and of a fibrous radiate mineral between felspar and olivine; that there is a typical gabbroid structure. It is well to remember that Grubenmann has stated * that the gabbroid structure may be a variety of the granoblastic structure. The presence of these characters inclines us to view the so-called "normal gabbro" not as an absolutely unmodified igneous rock. Now Grubenmann recognises † the difficulty in the separation of certain crystalline schists with massive texture from igneous rocks. But, however, if the gabbros are pre-serpentinisation in age, and if the schistosity be produced in the manner suggested, we would scarcely expect normal gabbro to remain as such, and we might expect part of the gabbro to be involved in pressures of the hydrostatic type. It may, therefore, be better to accept the small amount of evidence and recognise the affinity of the "normal gabbros," as well as the flaser gabbro and the gabbro schists, to the metamorphic types. If, on the other hand, the igneous character be maintained as dominant, the small area at Coverack must not be looked upon as normal, but as a relic of the original gabbro. The metamorphic, not the igneous, state is here the truly normal character. The troctolite at Coverack possesses saussuritised felspar, serpentinised olivine, and reaction rims, and, therefore, also possesses metamorphic traits.

There remain for comment the Kennack gneisses (pp. 119, *et seq.*) which Flett and other workers consider to be the crux of the Lizard problem, though we think that the serpentine has a claim to that distinction. The Kennack gneisses, however, present a distinct problem in themselves. Flett has brought forward strong evidence to show that these gneisses are metamorphosed igneous intrusions in the form of stocks, sills, dykes, veins, and networks into the original peridotite. If they be pre-serpentinisation they would necessarily be subjected to the same metamorphosing action as the gabbro dykes. The dykes will be foliated parallel to their length and the stocks parallel to their margins. Any peridotite blocks that had been caught up by the invading magma before the serpentinisation would yield to the serpentinising forces in the same manner as the large mass. Presence of the serpentine inclusions in the sills or gneiss is not necessarily evidence that serpentinisation occurred before the intrusions of the gneisses.

The complexity of the Kennack gneisses is due to the mixture of primary basic rock and primary granite rock. With regard to the "Blocky Gneisses," in which blocks of basic rock are included in granite gneiss, the fact that the blocks are seldom angular, but are usually rounded or lenticular, does not show that they were being dissolved by the granite magma. Where Flett records the evidence of acid magma diffusing into the inclusions and yielding an intermediate rock, we may only have a further example of metamorphic diffusion. In the "Blotched and Streaky Gneisses" the basic material may be again, as in other cases, the fragments of a disrupted and broken dyke. Such a possibility is suggested because this type passes into the "Flow Banded Gneisses," which may be an injection banding which has preserved its entity throughout the metamorphism.

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* Op. cit., vol. I., p. 79.

† Op. cit., vol. II., p. 19.

The granite gneiss, which occurs within the serpentine area and is intrusive into it, would be affected on its margin by the serpentinisation in the same manner as the gabbro dykes and Kennack gneisses. Flett describes (p. 41) how the older serpentine is often converted for a short distance from the contact into a soft greenish rock consisting mainly of talc and tremolite, with sometimes anthophyllite and chlorite. He considers (p. 142) that these contact phenomena are pneumatolytic changes due to hot vapours and liquids given off by the cooling gneisses. An analysis is quoted to illustrate the difference in composition between the tremolite rock and the serpentine. As, however, tremolite and talc are better known as metamorphic minerals than as pneumatolytic minerals, it is very probable that Flett is dealing with a metamorphic product rather than a pneumatolytic one. The observed difference in composition can be readily explained by metamorphic migration of material.

Summary.

The memoir that is criticised contains an account of the extraordinary number of rock types met with in the Southern Lizard. The area is one of exceptional metamorphism, yet it is considered that the study has been approached more from the standpoint of igneous rocks than from the standpoint of metamorphic rocks. This has occurred because the metamorphic rock has not been given the same individuality that is given to igneous and sedimentary rocks. An attempt has been made to state the metamorphic standpoint and to demonstrate the results obtained thereby.

The Lizard serpentine has been viewed as a metamorphic rock, foliated in part. We think that the term "fluxion banding" is in most cases a misnomer when applied to these metamorphic rocks, and that the term "flowing gneiss" is also founded on misconception. The foliation of the gabbros dykes which penetrate the serpentine can receive adequate explanation from the combined effect of the external metamorphosing forces that cause serpentinisation, and the internal pressure and heat developed by the serpentinisation of the original periodotite. The introduction of the term "injection foliation" is not necessary, and it does not assist the explanation of the remarkable dyke foliation.

Descriptions in the area have corresponded to the conceptions of metamorphic differentiation and metamorphic diffusion. Transition is observed between the serpentine and the adjacent hornblende schists. Diffusion types are also present in the so-called "intermingling of acid and basic magma" in the complex Kennack gneisses.

Epidosites, that are found in association with the Landewednack schists and with the green schists and granulites of the old Lizard Head series, can be considered as metamorphic differentiation products.

At present there is no evidence to discriminate in age between the Landewednack hornblende schists and the Traboe hornblende schists. The observed differences can be explained by a varying temperature factor during the metamorphism and by metamorphic diffusion. Caution is necessary in order that the rocks termed "gabbro" are not misinterpreted. The flaser gabbro and the gabbro schist are decidedly metamorphic rocks. It is also possible to consider the "normal gabbro" as a slightly metamorphosed rock, but if it be maintained that the "normal gabbro" is a true igneous rock it must be recognised that it is not the normal rock of the area but a relic gabbro. In the latter case it is a remnant of the original gabbro that has escaped metamorphism.

The foliation of the dykes and sills of the Kennack gneisses can receive the same explanation as the foliation of the gabbro dykes. Serpentine inclusions in the sills are not evidence that serpentinisation occurred before the intrusion of the gneisses. They are evidence that the gneissic sills are the metamorphosed equivalents of dyke sheets that invaded the original peridotite. Finally, talc and tremolite are not to be considered pneumatolytic products and associated with the intrusion of the granite gneiss into the serpentine. They are metamorphic products, and must receive a metamorphic explanation.

6.—The Value of Chemical Criteria in Identifying the Origin of Metamorphic Rocks.

We may perhaps be permitted to add to the discussion on the value of chemical criteria in determining the origin of metamorphic rocks. Bastin* has quoted authoritative opinion on the value of these criteria, and has summarised and discussed the characteristics of fresh foliated rocks of sedimentary origin. The features indicating sedimentary origin in a chemical analysis are set out by Bastin thus:—

1. Dominance of MgO over CaO is strong evidence.
2. Dominance of K_2O over Na_2O has lesser critical value, but is suggestive.
3. Presence of considerable excess of Al_2O_3 over and above the 1 to 1 ratio necessary to satisfy lime and alkalies.
4. High silica may be indicative when supported by other criteria.

When three or all of these relationships hold good the evidence for sedimentary origin may be regarded as practically conclusive.

With the appearance of Adam's and Barlow's memoir on the Haliburton-Bancroft area, the value of these criteria seemed to be lessened, inasmuch as Adams and Barlow maintained that precisely similar amphibolite rocks could be derived from both altered limestones and igneous rocks, and that there was no alternative. While we remain unconvinced in this respect this difficulty is not acknowledged.

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* "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments," E. S. Bastin, Journ. Geol., vol. XVII., 1909, p. 445.

Trueman* also discusses chemical criteria as well as the criteria of texture and of zircon grains. He finds that texture is not successful in determining origin, but he demonstrates the use of zircon grains, though this method can have only limited application. Trueman describes the alteration of quartzite into sericite schist at Waterloo, Wisconsin. The application of the zircon criteria confirms the chemical work of J. H. Warner, and shows that all gradations exist between the normal quartzite and the most highly developed sericite schist. The zircon criteria demonstrate that the sericite schist cannot represent a former argillaceous layer in the quartzite, nor has the change of composition been affected by the introduction of igneous material from without. With the development of the sericite schist he finds a simultaneous removal of silica, and he notices the presence of quartz stringers in some of the bands. The observation might, perhaps, be stated that the sericite schist with quartz, as a metamorphic differentiation product, is formed during the metamorphism of a quartzite under special conditions. Dwelling on the composition of the platy minerals that develop under the special conditions, he is inclined to attach small importance to Bastin's criteria, even though they are satisfactory in his particular case. The actual transfer of material is the difficulty to Trueman, whereas Bastin formulated his criteria on the supposition that no essential change occurred in chemical composition during the metamorphism.

Bastin† replies to Trueman's point, and further demonstrates the value of his criteria in special cases when used as an adjunct to textural and structural evidence. He then turns to the question of transference of material during metamorphism and acknowledges that the value of chemical criteria is part of the broader question of the actual extent to which transfer of material takes place.

Leith and Mead have devoted considerable space to this question in their recent publication‡ titled "Metamorphic Geology." These authors emphasize that the use of a chemical analysis in this respect depends on two fundamental assumptions, viz., (1) that the rocks before rock flowage (metamorphism) had a distinctive composition sufficient to identify them as sediments; and (2) that there is no essential change in composition during metamorphism. We think it will be generally admitted, with Bastin, that sediments do have, in the great majority of cases, a distinctive chemical composition, and that the crux of the problem lies in the second assumption.

At the outset of their discussion Leith and Mead assume that the criteria set forth for sedimentary origin by Bastin may be used conversely to prove igneous origin. But this assumption seems to be scarcely warranted from Bastin's paper. Leith and Mead then attempt to subject the criteria to rigorous proof by application to a number of analyses of sericite schists, weathered and hydrothermally altered acid and basic igneous rocks, chlorite schists and hornblende schists. In the tests they fix the critical value of the Al_2O_3 content at 5 per cent. excess over the 1 to 1 ratio with lime and alkalies, *i.e.*, with more than 5 per cent. excess Leith and Mead consider that the criterion for sedimentary origin is satisfied, and less than 5 per cent. excess indicates igneous origin. Yet Bastin has stated that a 5 per cent. excess is only sufficient to cause a suspicion of sedimentary origin and that a 10 per cent. excess is necessary to make the sedimentary origin extremely probable. With these interpretations of the meaning of the criteria, Leith and Mead find, as a result of the indiscriminate application to rock analyses, without any consideration of other metamorphic characters, that the chemical criteria have value only when carefully qualified and limited, and that they always fail when other criteria fail. It needs to be added that the applicability of the criteria to weathered and hydrothermally altered igneous rocks is not important, because it has yet to be shown that weathering before the development of foliated structure is not negligible, as assumed by Bastin.

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* "The Value of Certain Criteria for the Determination of the Origin of Foliated Crystalline Rocks," J. D. Trueman, Journ. Geol., vol. XX., 1912, pp. 229-258, 300-315.

† "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments," E. S. Bastin, Journ. Geol., vol. XI., 1913, p. 193.

‡ "Metamorphic Geology," C. K. Leith & W. J. Mead. Henry Holt & Co., New York, 1915, p. 226, *et seq.*

The problem can be simply stated in terms of metamorphic diffusion and metamorphic differentiation. Chemical composition may be a very important and helpful factor in tracing the history of a schist in those cases in which neither metamorphic diffusion nor metamorphic differentiation has occurred. If Bastin's criteria are satisfied in these cases, the rock is conclusively sedimentary in origin. If the analysis is identical with common and definite igneous rock types there will be strong probability of igneous origin. There will only be doubt where detrital rocks such as tuffs and arkoses and sediments with approximate igneous composition are possible.

If either metamorphic process is suspected then great caution is necessary. Should there be the metamorphic differentiation of a single oxide like quartz, the remaining oxides in the analysis will still bear the same ratios, and the criteria will avail as in the case of the sericite schist. In general, however, we will be unable to place reliance on these chemical criteria wherever metamorphic diffusion or differentiation has prevailed. The composition of the chlorite rock at Cape Denison satisfies the three sedimentary criteria, the biotite hornblende schist satisfies two of them, while the epidosite does not satisfy any. The criteria are valueless in the case of metamorphic diffusion and differentiation types, because such types possess metamorphic individuality alone. They possess neither the individuality of an igneous rock nor the individuality of a sedimentary rock. They possess a complex history, and have arisen during the metamorphism prior to which they did not exist as individuals.

The actual extent of these processes, and with it the extent of the limitation of chemical criteria, awaits further research. They do seem to be of more frequent occurrence than hitherto suspected. Yet these processes only have limited range, and therefore in the complete description of any one area we would normally expect to find parts which have been unaffected by the migration. Hence Bastin's criteria will apply to parts of an area, but which part ? This question will be more readily answered if it should subsequently be found that metamorphic diffusion and metamorphic differentiation products are restricted to a certain few rock types.

7.—Conclusion.

Our reference to other areas of metamorphic rocks may now be concluded by tabulating the different hypotheses appearing in the geological literature, which are founded on the transition between two rock types in metamorphic areas.

1. Intermingling of basic magma with acid magma.
2. Differentiation of an intermediate magma into a relatively basic portion and a relatively acid portion.
3. Local melting or refusion *in situ.*
4. Gradual assimilation of pre-existing basic sediments by invading granite or gneiss, producing amphibolite as the final product.
5. Production of amphibolite by the extreme metamorphism of a limestone.

In each case, except the last, the observed transition takes place, as at Cape Denison, between a granitic gneiss and a basic rock related to amphibolite. In all cases, as far as can be judged at present, the evidence submitted might be explained on the hypothesis of metamorphic diffusion.

CHAPTER VI.

THE MACKELLAR ISLETS.

Field Notes*.

The Mackellar Islets are a group situated nearly due north of Cape Denison in Commonwealth Bay (Plate XXXII.). The smaller members are normally covered with a thick ice cap built by the frozen spray, which is swept from the surface of open water by the incessant winds. The largest island is practically ice free, and consists of a low plain whose highest point is about 40ft. above sea level (Plate XXXIII., fig. 1). The surface of the islets is, generally speaking, flat, and forms a contrast to the miniature mountain area of Cape Denison. Where prominences are seen they are well rounded. No polished areas or striæ were found, but the surface is very smooth in places, and appears to have only been recently roughed up by frost action or other disintegrating agencies. The surface is everywhere covered with saline matter blown off the sea, and this may assist the disintegration.

No moraines of truly foreign boulders occur on the islets, but patches of roughly-rounded boulders of gneiss, similar to the "lower moraines" on the mainland at Cape Denison, are found. In fact the general appearance is similar to the lower rock belt at Cape Denison. Detrital gravel patches appear in a few sheltered spots; their appearance and situations suggest that they are probably submarine accumulations, and, if so, they supply some evidence of relative uplift.

The dominant rock is a grey gneiss very similar to that at Cape Denison, but it is more uniform in character and more granitic. At intervals there are finer-grained darker patches. Irregular fine-grained black patches and streaks (amphibolites) are also moderately frequent, but they are not so conspicuous as on the Cape Denison outcrop. The foliation is sometimes almost horizontal, and at other times nearly vertical. At the north end the gneiss is particularly massive and granitoid. The trend of the rock bars through the Mackellar group is in a direction between N.N.W. and N. by W. Transverse to this dominant structure is a fracturing in a direction W. by N. (nearly W.N.W.) which has led to the development of cross gullies and ravines.

Description of Rock Specimens.

The rock specimens from the Mackellar Islets consist of three specimens of a granitic gneiss and one of amphibolite.

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* The field notes are supplied by Sir Douglas Mawson.

No. 981.—This is the specimen of the dark amphibolite, showing massive texture with fine even-sized grains of hornblende and felspar. In section it shows affinities to the Cape Denison amphibolites, and its percentage mineral composition is—

Hornblende	34·5
Felspar	50·3
Epidote	6·5
Biotite	5·1
Sphene	2·4
Apatite	0·8
Iron ore	0·4
Calcite	present

This composition possesses marked differences from the Cape Denison amphibolites. The proportions of hornblende and felspar are approximately reversed. The composition is most like that of the epidote biotite schist (No. 153), except that the biotite is replaced in this rock by hornblende. The high percentage of felspar is reflected in the colour of the hand specimen, which is not the dense black of the Cape Denison rocks. A portion of the felspar is saussuritised, and an extinction angle in partly saussuritised crystals of 40° has been measured from the lamellæ, and hence it may be called labradorite. There is a considerable amount of clear felspar which may bear a trace of lamellar twinning and which has a refractive index often inseparable from the Canada balsam. This clear felspar is looked upon as albite. No quartz has been detected among the clear felspar.

The hornblende is a little paler in colour than in the Cape Denison rocks, but the bluish tinge is prominent. The edges of the crystals are more ragged and indefinite. Epidote is found in pleochroic crystals of the same size as the hornblende. It may be associated with the hornblende in a manner which suggests its derivation from the hornblende, and it may fringe the biotite crystals. Crystals with definite crystal boundaries may be set in the biotite plates, and they may contain a brownish nucleus of allanite.

The biotite appears in relatively large and broken plates, and has a greenish-brown colour in its darkest position. It contains pleochroic haloes. Sometimes it is fringed with a rim of opaque iron ore, which is in turn surrounded with epidote. This suggests that free iron oxide is set free in a reaction between felspar and biotite. Sphene and apatite are abundant accessories, and occasional plates of calcite are present and are included in the felspar percentage.

The rock may be called an albite amphibolite, and is placed in the family of albite amphibolites in the epi division of the Group of the Eclogites and Amphibolites.

The separation of the anorthite part of the molecule of the plagioclase, and the consequent production of the highly sodic felspar, has liberated more lime and probably accounts for the unusually high epidote percentage. In this respect this rock is different from the average Cape Denison amphibolite, but agrees with the exceptional case, No.5. At Cape Denison we find a high percentage of epidote with the high percentages of biotite and the low percentages of hornblende, whereas in this case, as in No. 5 before, we get a high percentage of epidote even with a low percentage of biotite. This difference is no doubt due to slightly different conditions during recrystallisation, which are reflected both in the composition of the plagioclase and in the epidote percentage.

No. 983.—No. 983 is an example of the chief rock type. It looks like a coarse, massive biotite granite in the hand specimen, showing quartz and felspar and biotite. The biotite flakes of the normal granite are replaced by aggregates of small biotites. The pink colour of the felspars is inclined to dominate the colour of the rock, and its general appearance is different from that of the grey granodiorite gneiss of Cape Denison.

Under the microscope there is little doubt that this rock has been subjected to metamorphic agencies similar to those interpreted in the Cape Denison rock, and it must be classed as a gneiss, not as a granite. The large crystals of quartz show strong cataclasis. Large crystals of felspar, probably orthoclase, have been replaced by granoblastic aggregates of microcline. A large crystal of orthoclase, which is cloudy with the development of sericite, encloses areas, with more or less rounded outline, of perfectly clear microcline which is certainly due to the recrystallisation. The crystals of plagioclase have not been found with a refractive index above that of basal quartz. They are interpreted as an oligoclase, being less calcic than in the granodiorite gneiss. Diablastic structure is often developed in the plagioclase while rounded and vermicular pieces of quartz may be set in the felspar. The felspar crystals become more noticeably cloudy in the crush areas.

The crush areas, produced by the grinding movement, can be recognised between two large crystals. Mortar structure, however, is not obvious, because recrystallisation has proceeded in the crush zones and caused the development of comparatively large granular crystals. The development of these even-sized crystals in the crush zones and the replacement of large crystals by granulitic crystals may be considered as a stage in the development of granoblastic structure in a completely recrystallised rock. Biotite is abundant in these areas and it is often accompanied by muscovite. These two minerals are nearly always arranged around the contours of the relic minerals. Sericite, epidote, and muscovite are intergrown with the biotite.

Large crystals of allanite, apatite, and sphene are accessory constituents.

The rock may be called a granite gneiss or an epi orthoclase gneiss. Compared with the granodiorite gneiss of Cape Denison there seems to be more orthoclase (or its equivalent) and a less calcic plagioclase.

The remaining specimens (Nos. 982, 984) have a finer grain than the preceding, and with a grey colour in addition they resemble, in outward appearance, the granodiorite gneiss of Cape Denison. Further, a slight schistose structure can be detected in the hand specimen. In section andesine, with its refractive index just above basal quartz, has been detected, and this is a strong point of resemblance to the granodiorite gneiss of Cape Denison. There is considerably less allanite and apatite than in the preceding type, No. 983, but pyrite, magnetite, and zircon are present. The mechanical structures are equally prominent, and possibly muscovite is more abundant, and sericite correspondingly less than in No. 983. The presence of andesine makes the rock a granodiorite gneiss rather than a granite gneiss.

CHAPTER VII.

CAPE HUNTER.

Sir Douglas Mawson has supplied the following notes on Cape Hunter, as the result of his visit on December 22nd, 1913 :—

" The rock exposure forming Cape Hunter is quite an imposing sight at close quarters (Plate XXXIII., fig. 2). The coastline is steep, and the rocks extend as a narrow belt, elongated in the direction of foliation. The rock itself is a phyllite, very uniform in character, but may pass into distinct sericite schists; narrow bands here and there are a little talcose. Representatives of similar rocks have been collected from the moraines at Cape Denison. The foliation and bedding closely correspond, wherever examined. The foliation is vertical and trends N. 20° W. Jointing along nearly horizontal planes is prominent. Weathering has developed gullyways at right angles and across the trend of the rocks.

" The maximum height of the exposure is about 90ft. The top has a rounded hummocky surface which has been once polished and striated. Where the polish and striæ have been preserved the trend of striæ is N. 45° E. to N. 40° E.

" The prevailing schist contains, in some places, a notable amount of iron ore finely disseminated. In other places talc is found or quartz is prominent, and along some bands considerable puckering is noticeable. Along the foliation stringers of quartz are common; and with the quartz are crystals of hematite, magnetite (?), epidote, chlorite, garnet (?), etc. Some veins carrying much epidote and a little fluorite cross the foliation and bedding of the phyllite.

" Compared with Cape Denison there is a noticeable paucity of erratics at Cape Hunter. A few of these, especially a grey gneiss erratic and a red granite erratic, are several tons in weight. The following rock types were noted among the erratics :— Red granite, grey granite, both coarse and fine-grained red porphyries, red gneiss and grey gneiss, garnet gneiss, a gabbroic rock, a dolerite or basalt, red sandstone (one specimen only). There is a complete absence of representatives of the metamorphic silicated limestones."

Specimen No. 911 is an example of the Cape Hunter rock, and it is a very fine grained, highly schistose rock with a bright sheen on the cleavage surface. In section there is a prominent crystallisation schistosity, and the structure is both finely granoblastic and blastopelitic.

Relic crystals of quartz, felspar, magnetite, and lenticles of quartz form the pseudo-porphyroblasts around which the schistose ground mass bends. Some of the larger crystals of felspar are sericitised, while others are very fine granulitic aggregates of secondary felspar. The ground mass consists of small flakes of brown biotite, white muscovite, granular epidote, quartz, clear secondary felspar, prisms of tourmaline, apatite and zircon, magnetite and pyrite.

The biotite and muscovite are frequently intergrown. Occasionally there are much larger crystals of muscovite, and these may be bent. All the small biotite flakes are parallel, so that as the stage is rotated they all occupy the dark position at the same time. The pleochroism is strong, and consequently the section looks dense in one position but quite thin in the other position. In the latter position the rarer tourmaline prisms are in their dark blue position and can readily be picked up. There is a considerable amount of fine granular epidote among the fine material and, like the muscovite, larger porphyroblasts occasionally appear. Clear secondary felspar has been detected among the fine quartz but is much less abundant than the quartz. Iron ore is abundant, and numerous small cubes of pyrite have been seen. Colourless crystals of apatite are present, and also rounded crystals with high polarisation colours and high refractive index like zircon.

The rock can be named phyllite.

As far as can be made out the crystalloblastic order is—Tourmaline-magnetite, pyrite-biotite, muscovite-epidote-felspar and quartz.

CHAPTER VIII.

MADIGAN NUNATAK.

The Madigan Nunatak is situated in Lat. 67° 8½′ and Long. 143° 20′, about 30 miles distant from Cape Denison. It lies on a ridge which slopes away to the north, reaching sea level at Cape Gray, 18½ miles distant. Its appearance is that of a small rock island rising above the ice plateau at 2,400ft. above sea level, and it forms a small jagged ridge of rock running north and south. It is 160yds. long and about 50yds. wide in the widest part, and it rises from the level of the ice sheet at the southern end to a height of about 60ft. at the northern end. Views of the Nunatak are given on Plate XXIV., figs. 1 and 2.

It is composed of gneissic rocks whose foliation strikes approximately north and south, coincident with the direction of the ridge. There is a steep anticlinal fold at the southern end (Plate XXVII., fig. 3), pitching slightly to the north. In contrast to the freshness of the rock exposures on the coast at Cape Denison, Cape Gray, etc., there is found considerable surface weathering. The surface is frequently brown and iron stained, and the felspars may lose their transparency. Frost action is prominent, and many of the cracks and joint planes are filled with moderately fine disintegrated material. There is no sign of recent glaciation and no glacial erratics or ice striæ are found on this area.

Two rock types are found on this area. One is a black massive plagioclase pyroxene gneiss or pyroxene granulite whose relation to the second type is not obvious in the field. It was noted that it seemed to form either a band whose trend cut at right angles across the foliation, or a band that may have been conformable with the anticline. Its boundary on either side was indefinite or obscured by the angular blocks tumbled about by the frost action. The second type is the more abundant acid gneiss, containing blue quartz and hypersthene. In the neighbourhood of the anticline it has a banded character, but in other parts the gneissic character, though evident, is less prominent.

PLAGIOCLASE PYROXENE GNEISS (PYROXENE GRANULITE).

The fresh specimens of this rock are black and massive with moderately fine and even granularity. Macroscopically felspar and pyroxene are visible. The weathered surface is discoloured by brown iron staining. So long as the felspar is sufficiently fresh to be transparent the dark colour of the pyroxene dominates the colour of the rock. When, however, the transparency is changed to translucency in the early stages of weathering, the whiteness of the felspar is noticeable, and the rock assumes a grey colour.

In section the rock (No. 794) has a granoblastic structure, which is modified by subsequent cataclastic structures. The average absolute grain size is approximately 0·30mm. The mineral composition has been determined by the Rosiwal method to be—

Felspar	42·5
Pyroxene	45·5
Hornblende	3·3
Iron ore	8·4
Biotite	0·3

The rock (Plate IV., fig. 1) is therefore essentially an aggregate of felspar and pyroxene grains, which are of approximately equal dimensions. Apatite is also present as a minute accessory.

The greater proportion of the felspar is untwinned. When lamellar twinning is found it is irregular, patchy, and often bent. There is often undulose extinction, so that the determination of the felspar by the use of extinction angles is not satisfactory. The refractive index of most grains is in the neighbourhood of 1·551 (nitrobenzol), in some cases above and in others below. In a few cases the refractive index is below 1·542 (nelkenol). These observations are explained by the presence of two plagioclase felspars. Sections of the plagioclase with higher refractive index may be found which possess two good cleavages, and are therefore considered to be normal to (OOI) and (OIO), and an extinction angle of 30° was measured. Hence we consider this plagioclase to be a calcic andesine. The second plagioclase with the lower refractive index is in much smaller quantity, and is considered to approach albite in composition. One fragment with fine lamellation was noticed to have a refractive index less than Canada balsam. The felspar crystals are often fractured, and show cataclasis. Mortar structure is common between two felspar crystals.

The pyroxene includes both orthorhombic and monoclinic forms. Hypersthene is readily detected in the thicker sections by the characteristic pink to green pleochroism. The form of the grains is granular. The colour of the augite is pale green, and it is on the whole fresh. It shows cataclasis like the felspar, but not so conspicuously. Strain polarisation may be found, and some crystals are fractured and show mortar structure. The crush zones may develop through a crystal. Many of the pyroxene crystals possess a border of finely pulverised pyroxene produced during the stress action. This crush border may pass out gradually into crushed felspar, and then an apparent transition from augite to felspar appears. Very often fine streams of granulated pyroxene tail out into the felspar and appear as a set of linear inclusions. Ilmenite often forms rims and borders to the pyroxene crystals, and the appearance suggests in itself that the iron content of the primary substance had been thrown out during the development of augite in the first metamorphism. In rare cases the pyroxene is dusty with small ilmenite inclusions.

The hornblende is green and has a granular shape. It is clearly developed from the pyroxene because the passage can be observed. That the hornblende developed before the crushing is evident from the presence of crushed borders on the hornblende crystals. Very rarely the normal hornblendisation of the pyroxene is replaced by glaucophanisation. Small amounts of the blue pleochroic glaucophane have been detected and are associated with the pulverised augite rather than with the large crystals. It is interesting to note that such change is recorded by Grubenmann* in the alteration of the pyroxene of eclogites during transition from one metamorphic zone to another.

The iron ore percentage is greater than in any of the Cape Denison amphibolites. The major portion is ilmenite, which is frequently associated with a reddish-brown mineral, probably rutile. Pyrite is also present. The lustre of the pyrite is bronzy red, and is suggestive of pyrrhotite. Large ilmenite crystals show crushing and pulverisation along the borders like the pyroxene. The reddish-brown biotite is scarce, but is always associated in curious aggregates with ilmenite. It is probable that these aggregates are produced here, as in other cases, by the interaction of hypersthene and felspar. The hornblende may be similarly associated with the ilmenite. The biotite flakes are sometimes bent, and were probably formed before the cataclasis.

The mechanical effects which are typical in the epi zone of metamorphism are a dominating feature of this rock, and mark the final metamorphic impress. Hence we name the rock an epi plagioclase pyroxene gneiss.

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* Op. cit., vol. II., p. 84.

Chemical Characters.

The following analysis of specimen No. 794 was made by A. G. Hall, in the Victorian Geological Survey Laboratory, under the supervision of P. G. W. Bayly. In the second column is placed an analysis of a hornblende norite from St. Thomas Mount, Madras, by H. S. Washington*.

	I.	II.
SiO_2	50·62	50·04
Al_2O_3	11·43	11·65
Fe_2O_3	4·43	2·63
FeO	11·11	15·76
MgO	6·87	5·58
CaO	10·90	7·89
Na_2O	1·75	3·08
K_2O	0·24	0·89
$H_2O +$	0·62	0·19
$H_2O -$	0·19	
TiO_2	1·42	1·93
P_2O_5	0·08	0·20
SO_3	nil	—
Cl	tr.	—
MnO	0·28	—
NiO, CoO	0·03	—
CoO	tr.	—
Li_2O	tr.	—
	99·97	99·64
Specific Gr.	3·076	

Group Values.							Projection Values.		
S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
54·3	2·0	5·1	31·5	7·2	—	1·0	1·0	2·7	16·3

The analysis demonstrates the affinity of this rock type to the amphibolites. The character of the felspar is reflected in the proportion of potash to soda and in the relation of both of these to the high lime percentage. The iron percentage is a little greater than in the Cape Denison amphibolites. The silicity is the mean of those of the two analysed Cape Denison amphibolites

When this analysis of the Antarctic rock is compared with that of the hornblende norite—a basic member of the Charnockite series of India—points of great similarity are noticed. The percentages of SiO_2 and Al_2O_3 are practically the same. The total iron is much the same in each case. The relative proportions of MgO and CaO are also the same, while there is large excess of soda over potash in both cases.

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* "The Charnockite Series of Igneous Rocks," H. S. Washington, Amer. Journ. Sci., vol. XLI., 4th Ser., 1916, p. 323.

Classification and Origin.

The Ozann group values place the rock in the group of Eclogites and Amphibolites in Grubenmann's classification. The projection values assign to the rock a position in the triangular diagram close to the mean group value of Group IV. (fig. 11).

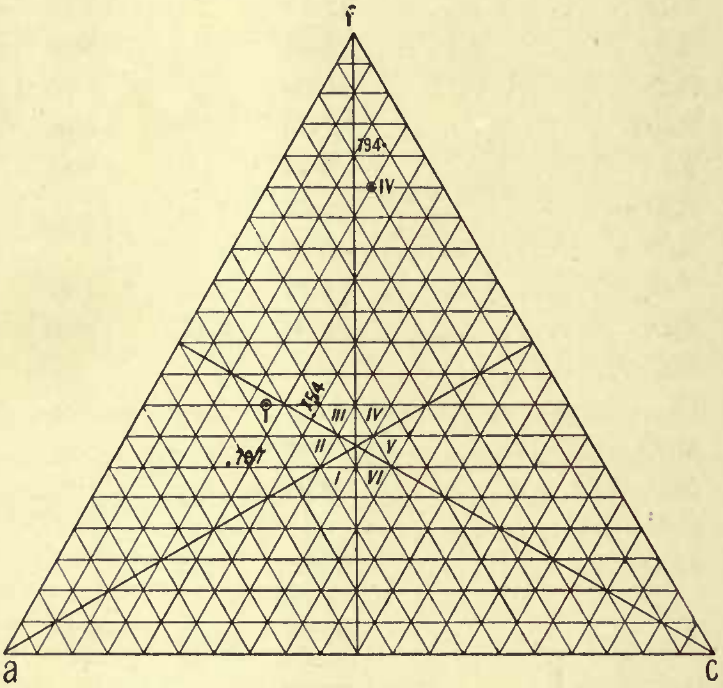

Fig. 11.

I. Mean Position of Group I., the Alkali Felspar Gneisses.
IV. Mean Position of Group IV., the Eclogites and Amphibolites.
797. Hypersthene Alkali Felspar Gneiss, Madigan Nunatak.
754. Garnet Hypersthene Alkali Felspar Gneiss, Aurora Peak.
794. Plagioclase Pyroxene Gneiss, Madigan Nunatak.

We admit the marked traits of the epi zone in the assigned name epi plagioclase pyroxene gneiss; but the rock bears a double metamorphic character. Reconstructing the outlines of the fractured minerals, it can be seen that, before the epi zone imprint was received, the rock consisted of a granoblastic aggregate of augite, hypersthene, plagioclase, and ilmenite, with a little hornblende and pyrite and biotite. As such it is identical with some of the Saxon pyroxene granulites, or the French pyroxene gneisses, or the Indian norites, whose metamorphic character will be subsequently affirmed from a comparative study with the basic rocks at Cape Gray and Aurora Peak. As such it is a member of the plagioclase augite family of the kata division of Group IV. Before the recrystallisation in the kata metamorphic zone we might judge from the chemical composition that the rock was either a gabbro or a diabase. In view of the large number of metamorphosed diabase dykes that are present in this region one would be inclined to consider that this rock is a diabase dyke which, suffering different metamorphic conditions, has been converted into a different rock type to the amphibolite at Cape Denison. Such is in accord with the field observation that the rock seemed to be a band, and such conclusion will be subsequently supported by correlative argument.

In the kata zone, then, the primary rock suffered its first and thorough recrystallisation, and the pyroxene and plagioclase and ilmenite were formed. In the transition from the kata zone to the epi zone we naturally find some evidence of the passage through the meso zone. The evidence is yielded by the alteration of the pyroxene into biotite and hornblende. It has been pointed out that the biotite flakes are often twisted and bent, and the hornblende sometimes granulated ; hence, like the pyroxene and plagioclase, they are secondary metamorphic relic minerals in the epi zone metamorphism.

The obscurity in the field concerning the boundary between the epi plagioclase pyroxene gneiss and the epi hypersthene alkali felspar gneiss may be readily explained by the presence of a metamorphic diffusion type which would cause a transition from one type to the other. Near the boundary the lighter coloured constituents become more prominent, and blue quartz may appear. At the same time the rock assumes a more schistose character.

Specimens showing the junction between the basic gneiss and the acid gneiss are present in the collection (No. 795). In these the junction is partly indefinite, and its position cannot be precisely marked in certain places. Small pieces of the dark rock are seen to be apparently detached from the parent mass and lie enclosed in the lighter-coloured rock. These junction specimens were no doubt collected from those parts where the junction was most obvious in the field.

HYPERSTHENE ALKALI FELSPAR GNEISS.

The second type of gneiss at the Madigan Nunatak is a coarse-grained grayish-white rock, in which the gneissic structure can be detected. Like the preceding type, it weathers to a brown colour. Macroscopically, one can see blue quartz, felspar, and smaller amounts of black hypersthene. There is considerable variation in the grain size of different specimens, and this is especially noticeable with respect to the dark hypersthene.

In thin section (No. 797) the schistosity is not noticed, but there is abundant evidence of crushing and cataclasis. Mortar, cataclasic, and diablastic structures are common. Quartz, orthoclase, and plagioclase form the bulk of the slide. Hypersthene, biotite, and ilmenite are important, though in a lower order of abundance. Zircon, apatite, and pyrite are accessory minerals.

Quartz units show strong undulose extinction, and are sometimes crushed so that a unit in ordinary light becomes a fine fragmentary aggregate in polarised light. In such cases a rude schistosity is evident, because many of the fragments are elongated in one direction. Every large quartz unit is separated from neighbouring crystals by crush zones.

Most of the felspar is orthoclase with perthitic inclusions of albite. The albite forms lenticular layers in at least two directions in the crystal. In cross section the albite is rectangular, and in longitudinal sections it appears as thin needles, while in some sections two sets can be seen crossing at an acute angle. In addition to the orthoclase and perthite there is a small amount of plagioclase with lamellar twinning and a comparatively low refractive index. It is considered as an albite oligoclase or an oligoclase, and it may contain perthitic inclusions of orthoclase. The lamellar twinning may only appear indefinitely in one corner of the crystal, or the laminæ may be bent and irregularly wedge out. In such cases undulose extinction is present, and there may be a poorly developed microcline structure. These observations are suggestive of secondary pressure twinning. However, the plagioclase is definite where the crush zones cut across the lamellæ, for in such cases the lamellæ must have existed prior to the crushing. The felspar shows the crush phenomena even more markedly than the quartz. The best examples of mortar structure are exhibited in felspar crystals which have straight fractures. A single crystal may contain one or more fractures, and each fracture filled with pulverised material. Mortar structure exists between a quartz crystal and a felspar crystal, but it is always less noticeable between two quartz crystals. Strings of minute inclusions are common and may extend into neighbouring crystals. Shear zones of sericite are often present, and become iron-stained during weathering. Sericite also appears along cleavage planes. Diablastic structure is very common in the crush areas, and there appear vermicular interlacings of felspars and of quartz and felspar (Plate III., figs. 1 and 2). Sometimes it is coarse and sometimes it is very fine, but in many instances it is obviously a secondary structure produced during metamorphism.

The hypersthene is present with its characteristic pleochroism and straight extinction. Like the quartz and felspar, it has suffered mechanical deformation, and one crystal is broken with the two pieces separated by a fracture zone. The crystals are sometimes bordered with a crush rim. It shows considerable alteration to a greenish, fibrous, serpentinous mineral, with moderately low polarisation colours, usually masked by the green colour. This mineral is similar to the alteration product of hypersthene in the Indian charnockites, which is described by Holland as resembling delessite*. The greenish mineral is a very constant associate of hypersthene in all the acid hypersthenic gneisses of Adelie Land. It is found in other cases to be intimately mixed with a pale-green biotite showing brilliant polarisation colours, and this rather suggests that it is delessite, a chloritic mica. On the other hand, cases have been noticed where the hypersthene passes through bastite into serpentine, whose appearance is quite similar to this green mineral. In part brown biotite and ilmenite seem to be developed from it. The biotite and ilmenite are practically confined to the hypersthene areas, and the three minerals are undoubtedly intimately associated. A very small amount of biotite seems to have developed with the alteration products of the felspar. The biotite always bears evidence of pressure, and the cleavage flakes are either bent or crumpled, or else in shreds. The ilmenite is also affected by the stress, and streaks of black ilmenite dust issue from the ilmenite crystals and traverse the fractured areas. When an ilmenite crystal partakes in the production of mortar structure the pulverised zone is darkened by the ilmenite fragments. Apatite and zircon are present in occasional and relatively large crystals which have been bent and fractured.

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* "The Charnockite Series," T. S. Holland, Mem. 28, pt. 2, G.S. India, p. 141.

Chemical Characters.

The following analysis of No. 797 was made by J. C. Watson in the Victorian Geological Survey Laboratory under the supervision of P. G. W. Bayly. In the second column is placed an analysis by H. S. Washington* of acid charnockite from St. Thomas Mount, Madras.

	I.	II.
SiO_2	72·38	77·47
Al_2O_3	13·39	11·00
Fe_2O_3	0·73	1·04
FeO	1·09	2·02
MgO	0·67	0·43
CaO	1·86	1·02
Na_2O	2·02	2·86
K_2O	6·57	4·14
H_2O +	0·44	0·20
H_2O −	0·12	0·05
TiO_2	0·40	0·26
P_2O_5	0·16	nil
SO_3	nil	—
Cl	nil	—
MnO	tr.	nil
Li_2O	tr.	—
	99·83	100·59
Specific Gravity	2·632	—

Group Values.							Projection Values.		
S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
79·8	6·7	1·9	3·0	0·3	—	1·7	11·6	3·3	5·1

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* Op. cit., p. 325.

The analysis is similar to that of a potash granite and it is considered that the chemical evidence of igneous origin is very strong in this case. The analysis bears witness to the high silicity of the rock with corresponding low percentages of iron, lime, and magnesia. The latter is absorbed in the hypersthene and its alteration products and is, therefore, some indication of the small quantity of hypersthene in comparison with the amounts of quartz and felspar. The relative amounts of TiO_2 and Fe_2O_3 confirm the record of ilmenite in the rock. The abundance of alkali felspar is reflected in the high percentage of alkalies, and the great excess of orthoclase is similarly reflected in the large excess of potash over soda.

Among the group values the high value of K corresponds with the high silicity, and the high value of A corresponds with the high alkali percentage. The projection values are such as to place the rock in the area of Group I. in the triangular projection (fig. 11).

Like the associated basic rock, the analysis shows considerable resemblance to the quoted analysis of acid charnockite. The silica percentage of the charnockite is nearly 5 per cent. greater; but this is not important, as Washington has drawn attention to such a range of variation among the acid charnockites themselves. The relative proportions of ferrous and ferric iron, of magnesia and lime, and of soda and potash are similar in each analysis.

The Classificatory Position.—The group values and projection values bring the rock into Group I., the group of Alkali Felspar Gneisses. The epi zone metamorphism is important and is revealed by the cataclastic and mortar structures. Before the epi zone metamorphism the rock consisted of a granular aggregate of quartz, orthoclase, a little plagioclase, and small amounts of hypersthene, biotite, and ilmenite with accessory apatite and zircon. As the schistosity is chiefly marked by the parallel arrangement of the hypersthene crystals it is obvious that the rock was schistose before the epi zone imprint. Further, if the inference that the biotite and ilmenite has been formed from hypersthene and felspar is correct, then such alteration took place before the epi zone metamorphism, because both biotite and ilmenite show marked mechanical effects. We must, therefore, recognise two metamorphic phases in the development of the metamorphic character of this rock. Parallel with the plagioclase pyroxene gneiss it will be subsequently affirmed that the primary rock was first recrystallised in the kata zone of metamorphism. As the rock ascended from the depths of the earth's crust and became subject to meso zone condition the hypersthene reacted with the felspar and produced ilmenite and biotite. Possibly here also some of the microperthite was formed and the diablastic structures produced. These metamorphic results were completed in the epi zone where the excessive mechanical effects were produced.

The rock may, therefore, be described as an epi hypersthene orthoclase gneiss, produced by the superposition of epi zone metamorphism upon a kata hypersthene orthoclase gneiss. The primary equivalent of the latter, judged from the chemical composition, was probably a granite.

The formation of the anticline* observed at the Madigan Nunatak is probably associated with the pressure movements which produced the crush structures. The banding of the anticline is noted by the foliated character of the rock.

Correlation.—The two types of gneiss from the Madigan Nunatak bear traces of similar metamorphic history. Both are rocks with prominent epi zone metamorphism which has followed kata zone metamorphism. In both cases the passage through the meso zone was fairly rapid, but it is noticed in the partial alteration of the pyroxene and the dissociation of the felspar.

The chemical likeness between both rocks and the acid and basic members of the Indian charnockite series has been pointed out. A discussion on this inter-relation will be subsequently presented.

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* The term "Anticline," as here used, is not strictly correct. An anticline is normally marked by the bedding planes of sedimentary strata. In this case it is marked by the foliation of a gneiss and might be distinguished as a foliation anticline.

CHAPTER IX.

AURORA PEAK.

Aurora Peak (Plate XXVI., fig. 3) is situated in Adelie Land in Lat. 67° 24′ and Long. 144° 12′ and is about 50 miles E.S.E. of Cape Denison. It is a solitary peak or nunatak rising above the snow plain on the west side of Mertz Glacier to a height of 1,750ft. above sea level. It is distant about 25 miles from the Madigan Nunatak, and similar rock types appear on both outcrops. It was visited by Madigan's sledging party in December, 1912, and our information comes from their report and from the examination of the specimens they brought back.

The similarity in rock types to the Madigan Nunatak is its outstanding feature. Here again there are two principal rock types, viz., a plagioclase pyroxene gneiss and a hypersthene alkali felspar gneiss, which are analogous in mineral content with the two types described at the Madigan Nunatak, differing only in mineral proportion and in structures. Whereas the rocks at the Madigan Nunatak are remarkable for their crush structures, the rocks at Aurora Peak are almost devoid of such features. Whereas the epi zone metamorphism is dominant at Madigan Nunatak, the meso zone metamorphism is equally dominant at Aurora Peak. Similar primary rocks have been metamorphosed in both instances under different physico-chemical conditions.

MESO PLAGIOCLASE PYROXENE GNEISS.

Specimen No. 759 is reported as a black band which cuts across the gneiss. In the hand specimen it is a fine-grained, dark-coloured rock with a weak schistosity produced by lenticles of felspar. The average absolute grain size is approximately 0·17mm. Its colour is black when fresh, and it grades up to a light-brown colour as the felspar becomes cloudy and iron-stained by weathering. The same minerals are present in the slide as in the analogous rock No. 794 from Madigan Nunatak. Hornblende is much more abundant, and there is a corresponding decrease in the amount of pyroxene from which it is derived. The proportion of felspar to ferromagnesia is practically the same in both cases. Apatite is also more abundant. The following proportions have been determined by a Rosiwal analysis :—

Felspar	44·8
Pyroxene	28·6
Hornblende	15·5
Iron ore	10·1
Biotite	0·3
Apatite	0·7

Thus there is in this rock nearly five times as much hornblende as in No. 794, and the transformation of pyroxene to green hornblende is correspondingly more obvious in the section. The formation of this hornblende is distinctly a meso zone character. The small amount of biotite is probably developed by the interaction of pyroxene with felspar. The felspar is again found in two varieties of plagioclase, and even though more than half is untwinned it is all believed to be plagioclase*. There is a calcic andesine or a sodic labradorite, and there is a much smaller quantity of a sodic or albitic plagioclase which in very exceptional cases possesses a refractive index less than Canada balsam. Ilmenite is found in indented and irregular grains. In all cases the pyroxene exerts its crystalline form against the ilmenite, so that in any aggregate of pyroxene and ilmenite grains the ilmenite is pushed into the interstices between the pyroxenes. It can therefore be understood, when the ilmenite is crushed and granulated in subsequent epi zone metamorphism as in No. 794, why the crushed ilmenite should appear as a border to the pyroxene crystals. Red-brown pleochroic rutile is sometimes associated with the ilmenite.

The absence of cataclastic structures and the important hornblende percentage influence the decision that this rock shows meso zone characters rather than kata zone or epi zone features. Its history will otherwise be the same as the related rock No. 794, and it has been a kata zone metamorphic rock consisting essentially of felspar, pyroxene, and ilmenite on which a meso zone metamorphic impress has been superimposed. It may therefore be called a meso plagioclase pyroxene gneiss (meso pyroxene granulite), or a hornblende plagioclase pyroxene gneiss (Plate IV., fig. 2).

Had the meso zone metamorphism been complete, all the pyroxene would have been converted into green hornblende and an amphibolite produced. The chemical composition must be similar to that of No. 794, and hence both chemical and microscopical characters reveal relation to the amphibolites. As many amphibolites are altered dykes rocks, this plagioclase pyroxene gneiss, similar to some of the Saxon pyroxene granulites, is probably a diabase dyke which has suffered metamorphism under kata zone conditions. The field observation that this rock appears as a band crossing the gneiss is confirmatory of such an argument.

HYPERSTHENE ALKALI FELSPAR GNEISS.

Specimen No. 754 is the type example of this rock, and it is a coarse-grey gneissic rock. In some examples the gneissic character becomes more prominent on the weathered surface. Macroscopically one can see thin lenticles of quartz set in a granular mosaic of felspar, and pink garnets and black hypersthene are also drawn out in layers in the direction of the schistosity.

In thin section the rock is granoblastic, with a tendency to a coarse crystallisation schistosity. Quartz units are built up of interlocking grains. There is little cataclasis. Felspar consists of untwinned individuals and lamellar twinned individuals. The former include both orthoclase and clear albite with perthitic inclusions of orthoclase.

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* The frequent absence of twinning lamellæ has been noted by Washington as a peculiarity of the hypersthenic rocks of India and allied areas; but we have noticed it in amphibolites and other metamorphic rocks.

The lamellar twinning is generally exceedingly fine, and the small extinction angle and low refractive index indicates an albitic plagioclase. Sometimes the felspar includes rounded blebs of quartz, and sometimes there is incipient diablastic structure. A certain amount of sericite has been produced from the felspar. The hypersthene is partly altered, and the same greenish, feebly pleochroic mineral (delessite ?) is present as before. It is also partly altered to enstatite. Brown biotite and ilmenite are also again associated in a significant manner with the hypersthene. Colourless to pale-pink garnet is present, and may be associated with the hypersthene. The garnet is found both in small and large crystals, which are partly idioblastic. Inclusions are not abundant in the garnet, but biotite, quartz, and ilmenite appear as such. Accessory grains of monazite or zircon are present.

Chemical Characters.

The following analysis of No. 754 was made by J. C. Watson in the Victorian Geological Survey Laboratory :—

SiO_2	69·42
Al_2O_3	15·03
Fe_2O_3	1·66
FeO	2·65
MgO	1·10
CaO	3·45
Na_2O	4·50
K_2O	1·39
H_2O +	0·65
H_2O −	0·07
CO_2	nil
TiO_2	0·35
P_2O_5	tr.
SO_3	nil
Cl	tr.
MnO	0·06
Li_2O	strong tr.
	100·33
Specific Gravity	2·685

Group Values.							Projection Values.		
S	A.	C.	F.	M.	T.	K.	a.	c.	f.
75·2	5·7	3·8	5·8	0·2	—	1·6	7·4	5·0	7·6

This analysis is very similar to that of the granodiorite gneiss of Cape Denison. There is a little less iron and magnesia in the case, but, except for the relation of one alkali to the other, there is no important difference. This rock is notable for its excess soda, though the alkali total is approximately the same in both cases. The analysis is more similar to the Cape Denison granodiorite gneiss (No. 11) than to the hypersthene gneiss (No. 797) of the Madigan Nunatak, to which it is closely allied in structure and mineral composition. Compared with this hypersthene gneiss there is more iron, magnesia, and lime, corresponding probably with the garnet and the different felspar. The alkalies furnish the most striking difference. Whereas there is a large excess of potash and orthoclase in No. 797, there is a large excess of soda and albite in No. 754.

The Classificatory Position.

The group values place the rock among the alkali felspar gneisses of Group I. These values illustrate the acidity of the rock and its high alkali value. The projection values, when plotted, give a position not greatly different from that of the mean group value of Group I., and intermediate between that of the hypersthene gneiss of the Madigan Nunatak and the granodiorite gneiss of Cape Denison (fig. 10).

Mineralogically this rock differs from No. 797 in the presence of garnet and the dominance of soda felspar over potash felspar. These differences do not carry the rock into a different schist group, because the relation between the alkalies does not enter into the classification. They are both hypersthene alkali felspar gneisses, while No. 754 is, in addition, garnetiferous. Cataclasis is not important in the Aurora Peak example, and we thus lose the dominating epi zone character found at Madigan Nunatak. Assuming for the present that the formation of the hypersthene and garnet belongs to the kata zone of metamorphism, we can infer that the rock is a kata zone rock. As, however, we have admitted the meso zone modification of its neighbour, the plagioclase pyroxene gneiss No. 759, we must consider what evidence of the meso zone conditions might be found in this rock. It is possible that some of the biotite has been derived from the reaction of garnet with felspar, or the biotite and ilmenite from the hypersthene and felspar. There is a significant association of these minerals, but it is not possible to give a sure interpretation from the study of this specimen alone. A breaking up of the garnet or the hypersthene might be viewed as a modification due to meso zone conditions. The abundance of perthite may be looked upon as further evidence.

We may, therefore, describe this rock as a garnet hypersthene alkali felspar gneiss developed in the kata zone of metamorphism and somewhat modified by the meso zone of metamorphism.

Without correlative evidence we must depend on the chemical evidence to indicate the nature of the primary rock. As far as can be determined there is no reason to suspect metamorphic differentiation or metamorphic diffusion, and the chemical criteria are valuable. The chemical composition is that of a well-known rock type, viz., a granodiorite, and this points to a primary igneous origin.

Comparison of other Specimens with the Type Specimen.

Other specimens from this locality tend to emphasise the subsequent meso zone impress. Specimen No. 758 possesses more prominent schistosity, partly due to the presence of prominent quartz lenticles on the weathered surface. In section the example is noteworthy for its more granoblastic character and its coarse perthite. In addition there are clusters of coarse brown biotite associated with ilmenite and with odd grains of hypersthene. The brown biotite with a green transition stage can be found developing from the hypersthene. Garnet is present, and biotite, without the ilmenite, is developing from the garnet, probably by reaction with felspar. These observations, therefore, tend to confirm the meso zone changes reported from the type example.

Two other specimens (Nos. 756, 757) were collected and reported by the sledge party to be variations in the gneiss, but less plentiful than the type example. These variations are found to consist of the gneiss with attached portions of metamorphosed aplitic veins. In each case the boundary is more or less destroyed by metamorphic diffusion, and consequently they are now all part of the gneiss. Specimen No. 757 consists of a granoblastic mass with weak crystallisation schistosity and well-developed diablastic structure. Here quartz and cloudy felspar (orthoclase, perthite, and a sodic plagioclase) form the bulk of the rock. Garnet is present and associated with biotite with alteration to chlorite. Ilmenite and zircon are common accessories, and a green spinel, probably hercynite, is present.

Specimen No. 756 is a coarser quartz felspar vein. It is more massive and possesses more cataclasis. The big crystals have produced in part a mortar structure. The junction with the gneiss is not noticeable in thin section. In a section across this junction it is simply noticed that one part of the slide carries garnet and biotite clusters with a little hypersthene, while these are absent in that part which represents the original vein.

There remains one other specimen from Aurora Peak. It has been described by the collector as a specimen illustrating the transition between the dark band (plagioclase pyroxene gneiss) and the hypersthene alkali felspar gneiss. It is rather a dark-coloured, banded specimen. Some of the bands are white, others consist of coarse quartz blebs set in a fine matrix, and others again of very fine black material. The white parts consist of quartz, felspar, more biotite than usual, occasional garnet and hypersthene with accessory ilmenite, zircon, and apatite. There has been considerable cataclasis in which big crystals have frequently assumed a lenticular shape. The crystals may be surrounded by a granulated zone, and biotite crystals may be set in that zone and tend to wrap themselves around the crystal. The dark bands appear to be slaty bands, out of which oval-shaped crystals of secondary quartz have arisen. On closer examination this is not so. Some of the apparently secondary quartz consist of crushed granulitic aggregates. Some are relic felspar crystals, while occasionally we find pale relic crystals of hornblende. Wrapped around them is a fine, dark pleochroic aggregate which is found to consist of minute biotite in which one can detect the incipient appearance of large biotite crystals mixed with some ilmenite dust. In places the dark bands and the finely granulitic material form a set of parallel bands and sometimes they penetrate the relic crystals. These dark bands of slaty appearance may possibly be formed by a continuation of the early stages of the same processes which cause the biotite to wrap itself around the crystals in the white portions of the rock. If, in addition, the dark zones represent zones of shear it may become possible to understand why they should be zones of excessive cataclasis and granulitisation. No large individuals exist in the crush zone which do not show strain polarisation and are not surrounded by a zone of granulitised material.

The early examination of this rock gave the impression that it represents the remains of a recrystallised sediment, and that the dark bands were originally slate. If this were so, and the field report is correct, it means either that the plagioclase pyroxene gneiss is a recrystallised sediment—a conclusion directly opposed to the study of the rock—or that there is a recrystallised sedimentary gneiss at Aurora Peak which escaped the observation of the sledging party. The specimen is not a transition type between the plagioclase pyroxene gneiss and the hypersthene alkali felspar gneiss as it is reported to be. The only possible explanation is that it represents a shear zone in which finely powdered biotite and ilmenite dust have dominated the colour. Large crystals of biotite could form, and it may be a stage of the process in which biotite crystals wrap themselves around crystals of quartz and felspar in the uncoloured portion of the rock.

CHAPTER X.

THE CAPE GRAY PROMONTORY.

DESCRIPTION OF LOCALITIES.*

The promontory terminating northward at Cape Gray is situated between Commonwealth Bay on the west and Watt Bay on the east. Its seaward edge is a continuous line of vertical ice cliffs whose monotony is rarely interrupted by rock exposures. The cliffs often rest on a rocky base and, whenever examined, they consist of consolidated snow showing distinct lines of stratification.

The promontory is thickly fringed with a large number of rocky islets which form the Way Archipelago. Some of these islands have a very striking shape. Some are steeply conical (Plate XXV., fig. 3) and rise out of the water with precipitous faces. One has its eastern face terminating in an absolutely vertical cliff, while another forms a sharp, angular wedge (Plate XXV., fig. 1) with its sides rising out of the water at an angle of 60°.

Rock exposures were reached from the mainland in three places, viz., Cape Gray, Garnet Point, and the Cape Pigeon Rocks, and the descent to them was made possible by the presence of a steep ramp of ice or snow (Plate XXV., fig. 4). In each case garnetiferous gneisses are found penetrated by altered basic dykes. As at Cape Denison the basic rock has been more readily eroded and occupies the gullies and depressions. It was noted that the islands appear to have the same general character as the rocks examined, and the subsequent visit to Stillwell Island in the motor launch substantiates this. Two islands seemed to be composed entirely of the black basic rock, while two others at the head of Watt Bay are light grey, almost white, in colour, and may consist of another phase of gneiss.

Compared with Cape Denison there is a noticeable absence of morainic material, but a few scattered erratics of granite and gneiss are found. Polished surfaces of rock are frequently noticed on the margin of the exposure, but only one instance of glacial striæ, trending about N.E., is recorded on the Cape Pigeon Rocks.

Cape Gray.

The rock exposure referred to as Cape Gray will, doubtlessly, be an island with further recession of the ice sheet. It is at present connected with the mainland by a narrow snow ramp, and a general view is shown on Plate XXIV., fig. 3. The outcrop is about 250yds. long and 100yds. broad, and it is elongated in an east and west direction. It is divided in the middle by a transverse gullyway which is occupied by a large basic dyke. At the western end of the exposure there are numerous dykes cutting through the gneiss and have a general trend a little east of north. The dykes repeatedly divide and unite with one another. They are mostly quite massive, and little evidence of schistosity is noticeable. The direction of foliation of the gneiss is a little west of north. In addition to the dykes, veins of quartz and felspar with garnet occur in two sets. A north and south set are faulted and displaced a few inches by an east and west set. No ice striæ could be found, but the margin of the island, extending back to a height of 20ft. above sea level, consists of well-polished rock. The remainder is rough and jagged as a result of longer exposure to atmospheric weathering; the lower zone has probably been relatively protected by a water or an ice-foot covering.

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* This description embraces the geological field report written conjointly by Lasceron and Stillwell.

Garnet Point.

Garnet Point is also approached from the mainland by a steep ice ramp. It is situated on the north-east portion of the promontory, and is about 10 miles distant from Cape Gray, and about five miles north of the Cape Pigeon Rocks. It is approximately the same size as the exposure at Cape Gray. A feature of part of this outcrop is the presence of abundant aggregates of garnet and mica, up to 2in. broad, which impart to the rock, even at a distance, a mottled appearance (Plate XXVI., figs. 1 and 2). The outcrop is divided by a steep transverse gully along which a large black dyke appears. The marginal zone of polished rock is again noticeable, and a waterworn pebble of the basic rock was found on a rocky ledge about 20ft. above sea level.

Cape Pigeon Rocks.

The Cape Pigeon Rocks are situated on the east side of the promontory and face Watt Bay. They are considerably larger than the preceding exposures, and form two rugged peninsulas which are separated by a narrow sea water channel, and which terminate seaward in a cliff up to 100ft. in height. A panorama of the northern peninsula is shown on Plate XXVIII. They are connected with each other on the landward side by a sloping causeway of ice. The bulk of the rock consists of a very coarse, grey, garnet felspar gneiss whose foliation trends 20° W. of N. It is traversed in numerous places by basic dykes which cut across the foliation. Two large dykes trending a little W. of N. are over 30ft. wide. One outcrops on the northern peninsula and one on the southern (Plate XXVII., figs. 1 and 4). From one of them a small dyke is seen branching off at right angles. They dip at a high angle to the west. Smaller dykes may be only 3in. wide. A large pegmatite vein was noticed. On the southern portion the rock is excessively contorted, and there are numbers of small dark amphibolite patches which are elongated and drawn out in the direction of the foliation.

Stillwell Island.*

Stillwell Island is one of the largest members of the Way Archipelago. It is a steep islet, with poor facilities for landing, and its maximum height is about 120ft.

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* This information has been supplied by Sir Douglas Mawson from his diary.

(Plate XXIX.). The general outline suggests ice cap erosion, but real smoothing is only seen up to 30ft. or 40ft. above sea level. At higher levels loose blocks are scattered about in a manner that indicates no ice sheet has recently passed over the island. No undisputed erratics are found, though several blocks illustrate a phase of the local gneiss not observed *in situ* in the island. Some very large blocks were noted removed short distances from their original position to situations where gravity could not possibly place them.

If the snow banks and ice foot were completely melted, the present island would probably be intersected by one or more sea-water channels. These channels are at the present time bridged by ice and undermined by the sea, and caverns are produced with rock walls and ice roofs. These breaks are in an approximate east and west direction, and remind one of cross-channel structure of the Mackellar Islets. They may correspond with the sea-water channel that divides the two portions of the Cape Pigeon Rocks.

The most conspicuous rock is a massive, light-coloured granitoid gneiss, often carrying abundant dark aggregates of garnet and mica, which are more or less spherical in shape and from ½in. to 2in. in diameter. Varieties of gneiss are also found without any garnet at all, and the highest part of the island is formed of an acid hypersthene gneiss. In crossing the islet areas are found consisting of more strongly foliated gneisses, and the trend of the foliation is a little west and north. Irregular bands of black gneiss, with dyke form, exist here as at Cape Denison, and some of them are full of fine garnet.

THE GARNET GNEISSES.

In the various outcrops the garnet gneiss exhibits foliation whose general trend is a few degrees west of north. Both Garnet Point and Stillwell Island are noted for the large garnet-mica aggregates which are relics of former complete garnet crystals.

Cape Gray.

At Cape Gray there is a rather coarse-grained rock (No. 784) which has a banded character in the hand specimen. It contains light-coloured bands of coarse felspar and garnet, appearing through a darker mass containing mica and garnet. The bands are irregular, being both thick and thin.

In the slide the rock is heteroblastic and the garnet crystals are much larger than the other constituent minerals. In part the quartz and felspar form granoblastic aggregates in which cataclasis is absent and diablastic structure is not common. The fresh character of this quartz and felspar appears in contrast to the finely granulitic character of the cordierite. The felspar is chiefly orthoclase and perthite. Microcline and some lamellar twinned sodic plagioclase are also present. The garnet is pink in the hand specimen and almost colourless in the section. It appears in small crystals as well as the large individuals, and usually has an irregular outline. There is a tendency to sieve structure, and the most common inclusions are ilmenite and biotite and, to a lesser extent, blebs of quartz and felspar. Biotite is present, both in large flakes and very small crystals. It is pleochroic from a reddish brown to a very pale straw. The small biotite crystals appear abundantly in cordierite. Cordierite is very prominent with its pleochroic yellow spots, and has the appearance of a fine granulitic aggregate produced by the crushing of a large crystal (Plate III., fig. 4). In addition to the biotite, small garnets, ilmenite and sillimanite are frequent inclusions in the cordierite, and the whole gives the appearance of a hornfels structure. Sillimanite is associated with the cordierite, both in the form of matted fibrous aggregates and prismatic needles. But it is not uniformly distributed, being more abundant in some slides than in others. Monazite is present, and when included in biotite or cordierite is surrounded by strong pleochroic haloes. Ilmenite is abundant, though more commonly included in the biotite and cordierite areas. Pyrite is also present.

The garnet and the cordierite provide the dominant characteristic of the rock, which may be called a garnet cordierite gneiss.

Garnet Point.

On Garnet Point there are two dominant types of gneiss in which are incorporated felspar veins bearing abundant garnet. The first type is rather a dark-coloured gneiss with abundant biotite. The second type is rather light-coloured and carries the large garnets which give the mottled appearance to the outcrop.

Specimen No. 772, collected from this locality, is a dark-coloured rock with feeble schistosity in the hand specimen. The abundant glistening biotite is sometimes aggregated in circular bunches, and felspar and garnet are visible. In thin section the rock is heteroblastic, and garnet is much more abundant in some sections than in others. In part it presents a granoblastic aggregate of biotite and plagioclase with some quartz, but there are, in addition, circular aggregates up to a quarter of an inch in diameter, consisting wholly of brown biotite. There are also granoblastic areas with grain size smaller than the average, consisting largely of biotite and quartz; and there are lenticles of quartz and felspar in which the diablastic structure may be prominent. The biotite is the most abundant mineral in all sections and usually has the same reddish-brown tint as in the previous case. It has a tendency to a parallel arrangement, except in the circular aggregates. It is remarkable in the possession of numerous and well-developed pleochroic haloes; and the nuclei of these haloes are sometimes large, and seem to be monazite rather than zircon. Apatite inclusions are also present in biotite but they are not surrounded by pleochroic haloes. The radius of the halo was measured by a micrometer eyepiece, and found to be 0·040mm. in several cases, thus agreeing with the ionisation range ThC and furnishing proof of thorium haloes. In several cases the haloes show the structure, described by Joly*, of an inner dark and an outer and lighter corona. The pupil of the halo is nearly always a bit fuzzy at the edge, and accurate measurement is therefore impossible. Some measurements give the radius of the pupil as 0·031mm., corresponding to the ionisation range of RaC, and this halo is to be considered as a compound thorium radium halo. Other haloes have been found to be 0·027mm., corresponding best with the range of ThX, while one case was found in which there was a suggestion of two coronas, and the radius of the pupil was 0·021mm., corresponding with the ionisation range of RaA. There are also small haloes with radius 0·013mm., which Joly accounts for by the slower moving ray of ionium, radium, or uranium. The structural features are not always very distinct, but the measurements indicate that haloes exist in the rock which are thorium haloes; others are radium haloes; and others are a mixture of thorium and radium. It is certain that the thorium haloes predominate. If monazite is the common nucleus in this rock, we should expect a mixture of thorium and radium in one halo, because monazite may contain up to 18 per cent. of ThO_2 as well as some radium.

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* "Pleochroic Haloes," Joly and Fletcher, Phil. Mag., 1910, p. 630.

The felspar is usually in clear grains with granular outline. It frequently shows good sharp twin lamellae and is found to be andesine. In the lenticles, which are comparatively free from biotite, the felspar is often more cloudy and shows conspicuous sieve structure as well as diablastic structure. Some untwinned orthoclase may be present. Quartz is clear and most abundant in the areas associated with garnet and biotite. The garnet has a very pale pink colour and is found in part as rounded grains with corroded outline, and in part as skeletal crystals noticeably associated with quartz and biotite. The larger garnet grains, which have suffered less alteration, may be surrounded by a pale greenish mica, distinct from the normal brown biotite. This pale mica may follow all the cracks that penetrate the garnet crystal, and it may pass by direct transition into the brown biotite. Pleochroic haloes are equally abundant in the two types of mica, but they seem to show more often the structure zones in the pale green type, *i.e.*, they are less often over-exposed. Moreover, the circular zone of the halo, situated in the pale green mica, is often changed to the brown type of biotite. Matted fibres of sillimanite may also be present in the quartz biotite areas. It seems evident that the garnet has reacted with the felspar, and possibly sillimanite, and has produced biotite and quartz. Such a change is quoted by Grubenmann* as an example of a zonal change in passing from the conditions of the kata zone of metamorphism to those of the meso zone of metamorphism. In other examples it will be considered that sillimanite is not a necessary factor in this reaction, but in this case sillimanite has been seen associated with the reaction areas.

Cordierite, with its pleochroic yellow spots, is also associated with the same areas of relic garnet and sillimanite. Within the granoblastic area of biotite and plagioclase coarse crystals of a colourless mineral may be found. It has a moderately high refractive index and oblique extinction in a section showing cleavage. Sections with imperfect cleavage are normal to a bisectrix, and the mineral is negative. There appears to be a simple twin whose two halves show a marked change of colour in parallel polarised light without difference in extinction. These characters cause the identification of cyanite.

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* Grubenmann, op. cit., vol. I., p. 52.

This identification has been confirmed by the preparation of more sections, in which we learn that the alteration of garnet to quartz and biotite is not the complete story of the change. Granoblastic areas are found which consist of cyanite and the pale green mica which is developed from the garnet. It seems, therefore, that the normal reaction, which produces quartz and biotite, may be replaced by one which produces cyanite and biotite. In the latter case there has been an excess of Al_2O_3 present, and possibly corundum has been involved. Ilmenite is not as abundant as in the Cape Gray gneiss, and monazite and apatite occur as accessories. The rock may be called a cyanite biotite gneiss produced from a garnet cordierite gneiss.

Specimen No. 770, obtained from the same locality, is similar to the preceding, though cyanite is not found in it. The hand specimen consists of the biotite gneiss with a piece of felspar garnet vein attached. In the slide the vein consists of colourless areas of orthoclase, perthite, soda plagioclase with abundant myrmikite and its diablastic structure. Occasional areas of ilmenite (with its alteration product leucoxene) are also associated with the biotite. As hypersthene has been found in similar veins in a similar locality (Stillwell Island) it is not at all impossible that these may represent the decomposition of hypersthene. In addition to the colourless areas there are large garnet areas in the hand specimen of the vein, with which biotite is associated. The biotite fills up the cracks and surrounds detached pieces of garnet, while the outline remains that of a large crystal. In the slide of this rock the relic areas containing sillimanite, garnet, and cordierite are more prominent than in No. 772. The sillimanite is found in coarse prismatic needles as well as in fibres, and is occasionally in parallel position with the biotite. There are also the aggregates of biotite and quartz which have certainly developed in the same way as No. 772. Sometimes the normal brown biotite is replaced by a much paler mica crowded with opaque magnetite dust. Some reaction has caused the separation of the iron content of biotite as magnetite. Associated with the biotite are numerous needles and grains of a yellow-brown mineral with high refractive index and double refraction, and with a tendency to be opaque. It is frequently included in biotite and is never surrounded by pleochroic haloes, and is considered to be a variety of epidote. Aggregates of muscovite are occasionally found with the biotite, while some of the biotite flakes are bent, crushed, and broken.

Specimen No. 777 is an example of the second type of gneiss from Garnet Point, and contains the large porphyroblastic garnets. The hand specimen is massive, and shows felspar and quartz, as well as the pink garnet. In the section the porphyroblastic garnets are found in skeleton form and penetrated by quartz and biotite. These may appear as inclusions in the garnet or else along the cracks and edges developed by interaction with the felspar. The biotite, as before, contains the pleochroic haloes, and is here again found to develop through a yellowish-green micaceous mineral. Areas of aggregated biotite and quartz with ilmenite are present, as in the preceding examples. Apart from the garnet areas, the rock consists of a granoblastic aggregate of cloudy plagioclase, orthoclase, microperthite, and quartz. The felspar is cloudy, partly through sericitisation and partly through saussuritisation. Scattered through these felspathic areas are small and large crystals of monazite, while in local patches there are numerous small crystals of corundum. The corundum is more or less rounded in cross sections, while longitudinal sections are long prisms with evidence of basal cleavage. The rock may be called a garnet felspar gneiss.

The Junction of the Cyanite Biotite Gneiss with Amphibolite.—Specimens showing the junction of this type of gneiss with the amphibolite are in the collection. Macroscopically there is a short and rapid transition from the gneiss to the amphibolite. The line of junction is straight, and by no means indented as it would be if the gneiss had been eaten away by the invading amphibolite. The dykes are relatively small and the transition can not readily be explained by assimilation.

Under the microscope there is perfect crystalline continuity across the junction, and hornblende appears and increases in quantity with the diminution of biotite and garnet (Plate III., figs. 5 and 6). The cyanite and quartz seem to travel further into the amphibolite than the biotite and garnet.

The gneiss in the specimens is similar to the biotite cyanite gneiss No. 772, except that the garnet is more abundant and the character of the cyanite is different. The cyanite possesses here pronounced lamellar twinning, and its polarisation colours reach the lower part of the second order colours. Quartz in the section never shows a higher polarisation colour than a very pale yellowish white, and hence the double refraction of this cyanite must reach at least 0·019. The highest recorded value for cyanite is 0·016. Yet it seems necessary to associate this mineral with cyanite. It is colourless, with a cleavage parallel to the twin lamellæ. Cross sections, which show indistinct twinning, show two cleavages, both of which are oblique to the direction of the twin lamellæ. Crystal outlines are completely absent and it appears in irregular plates with marked sieve structure. The abundant inclusions consist of biotite, garnet, quartz, felspar, and ilmenite. Its refractive index is about the same as the other cyanite. Extinction angles have been measured up to 28° from the lamellæ, but they are often less. In the region of hornblende it is found to pass by direct transition into hornblende. Part of an individual crystal may be green hornblende, and part the colourless cyanite, and, further, the cleavage continues indiscriminately through the green and colourless portion. The hornblende usually has a smaller angle of extinction, measured from the trace of the lamellæ. The regular arrangement of hornblende with the cyanite in the hornblendic part of the section is in contrast with the irregular inclusions of biotite in the cyanite on the biotite part of the slide.

The cyanite extends some distance out into the amphibolite, and some of it may be found in most sections of the amphibolite. Unfortunately, the number of specimens is limited, and the collection is too incomplete for us to be able to deal fully with this case of migration. Nevertheless, it is certain that the amphibolite dyke intruded the sediments, now represented by biotite cyanite gneiss, before the recrystallisation, and that the junction between the two has been rendered indefinite by the recrystallisation. It also seems probable that a migration of molecules has taken place across the original boundary during the metamorphism, and the position of the original junction is marked by the mixed rock. It also seems probable that certain simple minerals like quartz and cyanite are able to migrate further than the more complex garnet or biotite or hornblende. We may refer to this as another instance of metamorphic diffusion, and it would be very interesting to see how far this cyanite could be traced into the amphibolites. This we are, unfortunately, unable to do from the material in our collection. The specimens are small, and from them we can only determine that cyanite is found in amphibolite at least an inch from the apparent contact. All the specimens of this dyke show fragments of the attached gneiss.

Cape Pigeon Rocks.

Garnet gneisses are recorded in the field notes from this locality, but there are no specimens of it in the collection. The garnets are noted as being particularly abundant in part. A different phase of the gneiss with large porphyritic crystals of felspar is also recorded. Hypersthenic gneisses were collected from this locality and will be dealt with later.

Stillwell Island.

A garnet gneiss (No. 917), similar to the garnet felspar gneiss (No. 777) collected from Garnet Point, is obtained from Stillwell Island. The large garnet-mica aggregates are again a feature in the gneiss on the island. The mica associated with the garnet is, in most sections, the pale-greenish variety, from which the brown biotite is only feebly developed; but in one example (No. 939), collected a little below the summit of the island, the brown biotite completely replaces the greenish variety. The green biotite forms the marginal fringe to nearly every fragment of garnet, and there can be no doubt that the aggregates were originally complete crystals of garnet. Pleochroic haloes are abundant in the green mica, and we notice, again, that the alteration caused by the radio-active particle has caused transition to brown biotite. In such cases the brown biotite emphasises the halo area, and an example has been noticed where only the inner ring of a halo with structure is marked by the brown biotite.

This specimen shows in part more evidence of cataclasis than the Garnet Point example. Granulation of the quartz, which has developed with the mica from the garnet and mortar structure, are present, though not in any marked degree. Large garnets (No. 917*b*) occasionally show cataclasis and are then represented by a granular aggregate. The granulated garnet, like the granulated quartz, may be drawn out in a linear manner in the direction of schistosity. The plagioclase is very cloudy, and the diablastic and sieve structures are prominent. Large orthoclase and perthite may be traversed by lines of sericite. Occasionally we find areas of cordierite with its pleochroic spots associated with granular garnet and biotite; and sometimes the small crystals of corundum appear as in the related example. Ilmenite, pyrite, and epidote have been noted. The rock may be called, like No. 777, a garnet felspar gneiss.

Chemical Characters.

Analyses have been made of the garnet cordierite gneiss from Cape Gray and of the cyanite biotite gneiss from Garnet Point. The analyst is A. G. Hall, Victorian Geological Survey Laboratory.

	I.	II.
SiO_2	60·93	55·39
Al_2O_3	18·09	18·36
Fe_2O_3	1·88	1·76
FeO	5·55	6·81
MgO	4·54	4·74
CaO	0·90	2·79
Na_2O	1·78	3·36
K_2O	3·89	3·74
H_2O +	1·15	1·46
H_2O −	0·14	0·13
TiO_2	1·07	0·86
P_2O_5	tr.	0·14
SO_3	nil	nil
Cl	tr.	tr.
MnO	0·14	0·24
NiO, CoO	0·02	0·03
CoO	tr.	tr.
Li_2O	strong tr.	tr.
Total	100·08	99·81
Sp. Gr.	2·752	2·804

	Group Values.							Projection Values.		
	S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
I.	68·2	4·6	1·1	14·3	—	6·0	1·5	4·6	1·1	14·3
II.	62·5	6·2	3·3	15·9	—	2·6	1·0	4·9	2·6	12·5

I. Specimen No. 784.—Garnet Cordierite Gneiss, Cape Gray, Adelie Land

II. Specimen No. 772.—Cyanite Biotite Gneiss, Garnet Point, Adelie Land.

The outstanding feature of these analyses is the high percentage of alumina, a considerable excess over the 1 to 1 ratio necessary to satisfy the lime and alkalies. In addition there is, in both cases, a dominance of MgO over CaO, and of K_2O over Na_2O. Bastin's criteria of sedimentary origin* are therefore satisfied.

The total alkali percentage of No. 772 is high, and finds mineral expression in the abundance of biotite and of felspar. The felspar is less important in No. 784, and there is a greater dominance of K_2O over Na_2O than in No. 772. The great dominance of alkalies over CaO in each case is an important factor when considered with the silica percentage. The low CaO percentage of No. 784 means that there can be little lime in the abundant garnet and probably, also, little CaO in the plagioclase. In No. 772, where the plagioclase is more important, there is three times as much CaO as in No. 784, but there is still the large excess of MgO.

The high alumina percentage is reflected in the Group Value T, and the values for T are again indicative of sedimentary origin. T is lower in No. 772 because the higher alkali percentage absorbs more Al_2O_3. The value F, which expresses the ferromagnesian constituents, is very high in both cases. As a consequence the projection values are dominated by the excessive value of f. No. 784 occupies a position (fig. 12)

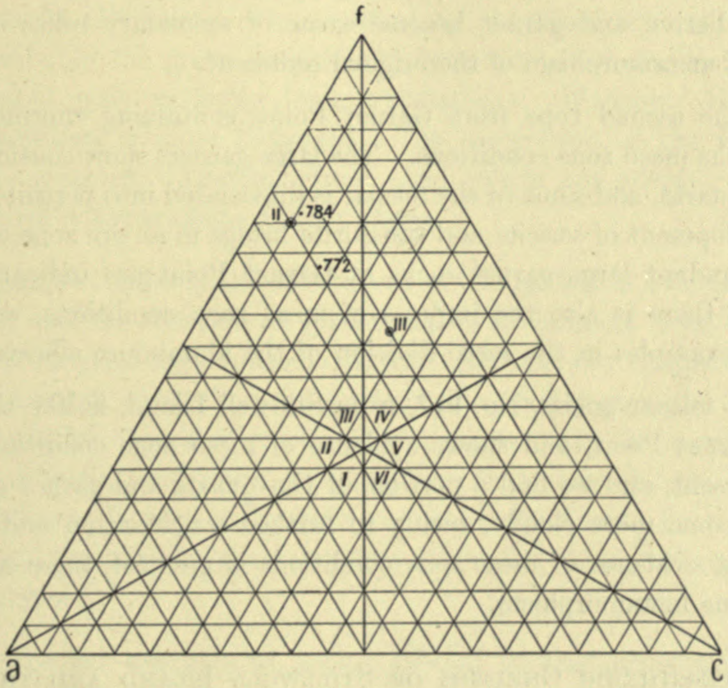

Fig. 12.

II. Mean Position of Group II., the Aluminium Silicate Gneisses.

III. Mean Position of Group III., the Plagioclase Gneisses.

784. Garnet Cordierite Gneiss, Cape Gray.

772. Cyanite Biotite Gneiss, Garnet Point.

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* "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments," E. S. Bastin, Journ. Geol., 1909 vol. 17, p. 445.

on the triangular projection close to the mean position of Group II., the group of the aluminium silicate gneisses. No. 772 also lies in the same area, but in a direction tending towards the mean position of the plagioclase gneisses.

Classification.

The group values, considered collectively, place both rocks in the group of the aluminium silicate gneisses. In all cases the values fall within the assigned limits of this group, except the value of T in No. 772, which is just below the lower limit (3·0). The other types from this region, viz., Nos. 770, 777 from Garnet Point, No. 917 from Stillwell Island, No. 785 from the Cape Pigeon Rocks, probably belong to the same group, though certainty is unattainable without a chemical analysis.

The dominating garnet and cordierite with sillimanite in No. 784 means that the recrystallisation of the sediment took place under conditions of very high temperature and great hydrostatic pressure, *i.e.*, under the conditions of the kata zone of metamorphism. No. 784 is therefore placed in the kata division of the aluminium silicate gneisses. In the rocks Nos. 772, 770 from Garnet Point it has been noticed that the garnet and felspar with, perhaps, sillimanite have been replaced by biotite and quartz. This change is considered to occur in transition from the kata zone to the meso zone. When the meso zone metamorphic conditions are dominant, the areas of sillimanite, cordierite, and garnet become areas of secondary relics and indicate the double phase of metamorphism of the original sediment.

No. 777, the second type from Garnet Point, containing enormous garnets, also shows trace of the meso zone conditions. The large garnets show considerable alteration to biotite and quartz, and some of the felspar is dissociated into perthite and myrmikite. The small development of sericite and saussurite brings in an epi zone element. Hence, though the abundant large garnet rocks at Garnet Point are indicative of kata zone metamorphism, there is also the impress of meso zone conditions, which is sufficient to place these examples in the meso division of the aluminium silicate gneisses.

The garnet felspar gneiss, No. 917, from Stillwell Island, is like the garnet-felspar gneiss from Garnet Point, and shows evidence of meso zone conditions. In this case cataclasis is present, and we find a portion of the quartz and garnet granulated. The felspar has become more cloudy, owing to further sericitisation and saussuritisation. Hence, while the evidence of meso zone conditions is greatest, there appear the initial stages of epi zone metamorphism.

THE ACID HYPERSTHENIC GNEISSES OF STILLWELL ISLAND AND THE CAPE PIGEON ROCKS.

In addition to the garnet felspar gneisses a second type, related to the acid hypersthene gneisses of Madigan Nunatak and Aurora Peak, was discovered on Stillwell Island and the Cape Pigeon Rocks. In one case on Stillwell Island this type of gneiss appears in dyke form. The same form of occurrence is strongly suspected at the Cape Pigeon Rocks, and similar rocks can be remembered at Garnet Point, though no specimens are in the collection.

Stillwell Island.

No. 949 is an example of this rock type, and was collected from a fine-grained band several inches wide, which crossed the gneiss irregularly near the summit of the island. This specimen is a rather dark-coloured rock with a vitreous lustre. Quartz and felspar are visible with a lens, and specks of pyrite are sprinkled unevenly through it.

The section consists of an even-sized granoblastic aggregate of quartz and felspar, through which grains of pyroxene and its associated biotite and ilmenite, pyrite and apatite are scattered (Plate III., fig. 3). The average absolute grain size is approximately 0·20mm. There is a general absence of crystal boundaries, and the manner in which blebs of quartz are set in the felspar is clearly metamorphic. The felspar is very clear and unaltered, and includes orthoclase and plagioclase. Lamellar twinned individuals have a refractive index often above basal quartz. The large extinction angle, measured from the trace of the lamellæ, is 20°, and hence the felspar is andesine. The pyroxene is largely hypersthene, and only a few grains do not possess straight extinction[*]. The pale-pink to pale-green pleochroism is very marked. The same green serpentinous alteration product which appears associated with the hypersthene in the Madigan Nunatak and Aurora Peak gneisses is found in this rock. In part biotite and ilmenite are developed in its alteration. The biotite may be mixed with the green alteration product, but probably the green mineral has developed after the biotite, as the latter may be associated with perfectly fresh hypersthene. Whenever the green mineral appears the alteration is more advanced. The association of the ilmenite with the biotite is fairly constant. Apatite, zircon, and pyrite are accessory minerals. The rock may be called a hypersthene felspar gneiss.

This rock has not suffered the subsequent crushing that is evident in the Madigan Nunatak gneiss, and the absence of garnet makes it different from the Aurora Peak gneiss. It therefore possesses, without any modification, the characters of the Indian charnockite[†]. A rough determination of its specific gravity gave the value 2·67, which is the same as that for normal charnockite, and greater than the specific gravity of the Madigan Nunatak gneiss, and just a little less than that of the Aurora Peak gneiss. Its composition would not be very different from that of the Aurora Peak rock, and would, therefore, possess the igneous characteristics which are in agreement with the dyke form of its occurrence.

No. 979.—Another example of gneiss, related to the preceding charnockite-like rock, is No. 979, which was collected about 150yds. from the boat moorings at Stillwell Island. In the field it was noticed to be unusually free from garnet.

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[*] Grains of pyroxene with apparently oblique extinction have been shown by Washington (Amer. Journ. Sci., vol. XLI., 4th Ser., 1916, p. 323) to possess the optical character of hypersthene. This effect is ascribed to the development of a cleavage other than the usual prismatic cleavage.

[†] The charnockite series will be discussed later. A special rock name is desirable for the acid hypersthenic gneisses, yet Holland has definitely asked that the name charnockite should not be used for extra-Indian rocks. Still, if it be acknowledged that the Indian charnockite series does not consist merely of phenomenal igneous rocks but of definite metamorphic types, then it may be suggested that, with Holland's permission, "charnockite" should supply the need.

In the hand specimen it is a coarse brownish-coloured rock, showing quartz, felspar, and hypersthene, and a little biotite. In section it is a coarse granoblastic aggregate. The quartz shows a little granulitisation. The felspar consists of both twinned and untwinned varieties. Peg structure and diablastic structure are common in the felspar. The development of the diablastic structure by the dissociation of plagioclase crystals *in situ* is very plain in some instances. Lamellar twinned felspar has again a refractive index occasionally higher than that of the basal quartz, and it is probably andesine.

A brown biotite is the most abundant ferromagnesian mineral. It may be associated with ilmenite, and it is found in the hypersthenic areas. The hypersthene in the section is largely decomposed to the serpentinous greenish alteration product. Biotite is intimately associated with the serpentine and seems to develop from it in a pale-green form. Sometimes the hypersthene loses its iron content, becomes colourless, assumes lower polarisation colours, and changes into enstatite. In places a very pale-green biotite is associated with the hypersthene, and this seems again to be an intermediate stage between brown biotite and the green delessite. Occasionally large crystals of apatite and zircon are present. Grains of ilmenite and fragmentary garnet are near the hypersthene. The garnet may form fragmentary rims around the biotite, and occasionally the biotite is grouped in radial sprays.

In a second slide of No. 979, cut from the opposite end of the specimen, the sprays of radial biotite are more prominent surrounding the ilmenite nuclei (Plate V., fig. 3). Some of the biotite flakes are associated with fan-shaped felspar vermiculæ, as in Plate V., fig. 4. The association of quartz with the biotite sprays is also noticeable, especially in the aggregates of small basal biotites and quartz, which are in some cases cross sections of biotite sprays. This slide also contains a plate of basal biotite which is surrounded by a rim of later biotite straws set in quartz, which in turn has a thin coating of iron ore (Plate VI., fig. 4). The garnet is more abundant in this slide and may be detected as fragmentary rims around ilmenite as well as biotite. These features will be found to be better developed in the next example, No. 947.

In this case we have also noticed large crystals of untwinned plagioclase with inclusions of orthoclase distributed in the same manner as the schiller inclusions in olivine in peridotite from the Isle of Rum*. The appearance is not unlike a graphic structure, but it is distinct from the vermicular intergrowths in the same slide. The inclusions of orthoclase have a considerably lower refractive index than the untwinned plagioclase (andesine), and the larger pieces contain minute fusiform inclusions of a felspar with higher refractive index. The crystal plate of plagioclase possesses cleavage which extends in places across the orthoclase inclusions, and the extinction angle, measured from the cleavage, is 4°. When the stage is rotated in the opposite direction an extinction angle of 3° is measured in the orthoclase inclusions. The complete recrystallisation of this rock, together with the abundant metamorphic felspar intergrowths, indicates that this graphic-like structure is also of metamorphic origin, and possibly connected with diffusion phenomena.

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* "Natural History of Igneous Rocks," A. Harker, p. 258.

The rock may be described as a meso-hypersthene felspar gneiss. We may conclude that the hypersthene is less in quantity than in No. 949, because more of it has reacted with the felspar to produce biotite and ilmenite. It is certain that the type is more closely related to No. 949 than to No. 917, the garnet felspar gneiss. It has only been reported as indefinite bands associated with the garnet gneisses, which are considered to be sedimentary in origin, but it possesses undoubted affinities to igneous rocks and to No. 949, which occurs as a dyke. It is quite likely, therefore, to be the metamorphosed equivalent of an acid dyke whose identity has been wholly or partially lost by the operation of metamorphic diffusion.

No. 947.—Another example of the hypersthenic gneiss was obtained from the summit of the island. It is a coarse rock similar in outward appearance to No. 979. The brownish colouration of the rock is a little more prominent, and, at the same time, more like the brownish coloured rocks of Madigan Nunatak. While related to the preceding example, No. 979, it differs from it in possessing much more garnet, more pyroxene, less biotite, and very little quartz. Yet a rough determination of the specific gravity gave 2·74 in the first case (No. 979) and 2·76 in the second (No. 947).

The place of the quartz in No. 979 is taken by areas of untwinned felspar (orthoclase) with cryptoperthitic inclusions. Augite, as well as hypersthene, is present. The pink garnet appears in two ways: it may appear first as large crystals with felspar, biotite, and ilmenite inclusions, or it may appear as granular garnet surrounding ilmenite, biotite, and hypersthene. The garnet rims around the ilmenite and biotite clearly follow closely all the irregularities in shape of the ilmenite and biotite nuclei (Plate V., figs. 5 and 6). Biotite and ilmenite are often associated with the pyroxene, and have no doubt been formed from it in part in the familiar reaction with felspar. The biotite may partly enclose the pyroxene and it may fill cracks and indentations in the pyroxene crystals. Further, as the garnet rims around the pyroxene may be in part separated from the pyroxene by biotite, we can fairly safely conclude that an explanation of the garnet around the biotite will provide an explanation of the garnet rim around the pyroxene. Again, we can find crystals of ilmenite symmetrically enclosed by a biotite zone, and, if this biotite zone were replaced by a garnet zone, we should get the garnet rims around ilmenite as are observed. Consequently, an explanation of the garnet-biotite reaction will also provide an explanation of the garnet zone around ilmenite. This conclusion is supported by the discovery of an aggregate in which an ilmenite crystal is surrounded by biotite, and this in its turn is practically surrounded by garnet, while pyroxene crystals jut against it in part.

It is therefore clear that biotite is on one side of the equation and garnet on the other. Sometimes outside the garnet rim a change in character of the plagioclase is quite evident. Hence the plagioclase may be considered to take part in the reaction and to supply a lime molecule which may enter the garnet. The following equation shows that for average compositions of biotite and garnet the change is chemically possible, and at the same time an explanation why the quartz of the related type (No. 979) is replaced by orthoclase in this example (No. 947)[*].

$$\underset{\text{Biotite}}{(KH)_2\,(MgFe)_2\,Al_2\,(SiO_4)_3} + \underset{\text{Anorthite}}{CaAl_2\,Si_2O_8} + \underset{\text{Quartz}}{4Si\,O_2}$$

$$\rightleftharpoons \underset{\text{Garnet}}{2(MgFe)O,CaO,\ Al_2O_3,\ 3SiO_2} + \underset{\text{Orthoclase}}{2KAl\,Si_3O_8}$$

The related rock (No. 979), in which there is very little garnet but much quartz and plagioclase, can then be explained as a rock type in which the biotite side of this equation is expressed. No. 947, in which there is considerable garnet and orthoclase and practically no quartz, may be looked upon as a rock type in which the garnet side of this equation is expressed.

We have interpreted the reaction of the hypersthene with felspar in these hypersthenic rocks to biotite and ilmenite as associated with a change of kata zone conditions to meso zone conditions. If, after these changes, the biotite reacts with quartz and felspar to produce garnet and orthoclase, we should, on the same reasoning, interpret the cause as a reversal to the kata zone conditions. For this we cannot imagine any variation in the depths of the earth's crust, because there is no similar evidence in any other variety of gneiss on Stillwell Island. We can only imagine that the temperature and pressure have been increased locally, possibly by neighbouring chemical reactions which have liberated heat and caused expansion of volume. If this were so the area subjected to the reverse conditions would be highly localised.

The specimen No. 947 is an irregularly shaped piece about 3in. long and, roughly, 1½in. square in section. A second section was cut from the opposite end of the specimen, distant 3in. from the first section. In this section no garnet is found, but large pieces of quartz. Hypersthene is present, again showing some alteration to ilmenite and biotite, but none of the biotite is rimmed with garnet. This result was surprising, and a third section was cut from the middle of the specimen, half-way between the two previous sections. In this middle section some garnet is found, but less than in the first section. It again borders biotite in the same remarkable manner. There is some quartz in the section. We have also noticed in this section a large crystal of pale-green mica with included ilmenite. This green mica is evidently an intermediate stage between delessite and biotite, but it is not possible to say in which way the reaction is going. Hence the supposition of the highly localised distribution of the garnet rims seemed to be confirmed.

The rock may be described as a hypersthene alkali felspar gneiss, in which the hypersthene has first partly changed to ilmenite and biotite. This change has been followed in localised portions of the rock by a partial reaction of biotite with quartz forming garnet and orthoclase.

Similar conclusions may be formed about the primary igneous origin of No. 947, as in the case of No. 979.

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[*] The (KH) molecule is reckoned as K_2 for simplicity. In the analyses of some biotites the K_2O is in great excess over the H_2O, and this is assumed to be the case here.

Cape Pigeon Rocks.

The hypersthene gneiss from the Cape Pigeon Rocks possesses many of the peculiarities noted in the preceding rocks from Stillwell Island. The specimen, though a little larger than No. 947, is no more than 3½in. long, and reveals the same remarkable variation in mineral content. Four sections cut from different portions of the specimen have been necessary to understand the character of the rock. These will be dealt with separately in order to again illustrate this variation. A rough determination of the specific gravity of the specimen No. 785 gave the value 2·75, and, therefore, its total composition is likely to be very similar to the composition of No. 947 or No. 979.

No. 785 (1).—No. 785 (1) was the first slide cut and examined from the specimen from the Cape Pigeon Rocks. In it there are only scattered fragments of garnet which has been largely replaced by biotite and quartz. A crystal of ilmenite often occupies the central position of the biotite aggregates as before. The larger biotites are sometimes bent or crushed, but they often open out into radial sprays set in quartz, which again enter into the fan-like myrmikoidal intergrowths of felspar. In other cases we get aggregates of small biotites with small quartz crystals. Pleochroic haloes are still common. The felspar is often cloudy and in part there is a good deal of sericite. In part the orthoclase is transformed into microcline. The plagioclase has, in most cases, a refractive index less than quartz and a small extinction angle, and is probably an oligoclase andesine. Some of it includes the common blebs of rounded quartz, and it frequently presents a diablastic structure. Along the junction of two felspar crystals we may find one of them bordered with a diablastic zone. In one instance where the diablastic structure has developed in a corner of a crystal, the twin lamellæ can be traced from the unaltered part through the diablastic area. Some of the plagioclase is saussuritised, and epidote is found both in sporadic grains and in the finely granular form with the saussurite. Chlorite is more abundant in this slide than in the others. Apatite appears in fairly large crystals, and pyrite and zircon are also accessory. No hypersthene is present; and on this description alone the rock would have to be named a biotite felspar gneiss.

No. 785 (2).—The slide No. 785 (2) is cut from the opposite end of the specimen, distant 3½in. In general, there is less chlorite, epidote, saussurite, or sericite than in the preceding slide. The garnet rims are well developed, and these, with the presence of hypersthene, indicate the relation of the rock to the hypersthenic gneisses of Stillwell Island. In the hand specimen there is nothing to indicate this variation. The igneous origin of this rock type is further evidenced by the large, well-defined crystals of apatite and zircon.

The hypersthene possesses a beautiful and intense pleochroism from pink to green. The depth of the pleochroism in hypersthene is usually associated with the iron percentage; but when one recalls the pleochroism of the titaniferous augites, it seems probable that the deeply pleochroic nature of these hypersthenes may be partly due to the TiO_2 content. The hypersthene may contain ilmenite inclusions, which are situated either irregularly or in planes. Occasionally the hypersthene loses its colour and pleochroism, assumes the lower polarisation of enstatite and changes into enstatite. Sometimes it is partially replaced by a platy brown mineral with the deep red brown colour of biotite but with very low polarisation colours. This brown mineral is an iron-stained serpentine.

Biotite is again abundant and appears in large platy crystals, in close aggregates of smaller crystals surrounding ilmenite, and as small crystals set in quartz. The fan-shaped biotite sprays may appear in the zone around ilmenite or with the biotite plates. Some of the biotite flakes are crushed and bent. Sometimes the biotite plates possess a dark border in which the integrity of the plate is broken. A slight perforated appearance develops and the dark colour is due to the separation of minute crystals of iron ore. It is an alteration which is either associated with the crush phenomena or else with the reaction which produces the biotite sprays. A further state is noticed where the biotite has completely lost its brown colour, though still surrounded by a fragmentary garnet rim. It has assumed a pale greenish colour and is dotted with small magnetites (or ilmenites) but still retains its bright polarisation colours. Residual patches of brown biotite may remain in the pale biotite, and as chlorite is present in the slide this may be interpreted as the passage of biotite into chlorite.

A feature of this slide is the presence of garnet rims similar in nature to those in No. 947. Apart from the rims, garnet only occasionally appears in moderate sized crystals. The garnet rims may surround biotite and hypersthene, and are usually composed of small, idioblastic crystals. The rims have not been observed around ilmenite as in No. 947, but an excellent example is found of an ilmenite nucleus, surrounded by biotite, which in turn is surrounded by a garnet rim (Plate VI., fig. 1). We also find the hypersthene surrounded by biotite and this in turn by garnet (Plate V., fig. 2). A thin layer of orthoclase may exist between the garnet and the biotite, but it is often absent. The garnet may come into direct contact with the hypersthene, and may even penetrate the hypersthene in seams. As biotite is often intimately mixed with the hypersthene it is possible, in many cases, to still explain the presence of the garnet in the hypersthene by a biotite-plagioclase-quartz reaction as in No. 947; but the examination of the fourth slide of this specimen proves that this explanation is inadequate in certain cases. The biotite-plagioclase-quartz reaction still explains the garnet rims on the biotite, but all the garnet is not so formed.

We find here, also, that the garnet rims surround aggregates of biotite and quartz (Plate V., fig. 1). Some of these have a definite rectangular outline and others may be irregular or approximately hexagonal or octagonal. The aggregates are very often without ilmenite, but they may enclose fragments of enstatite. The definite outline indicates that they formerly surrounded a single crystal, and that they existed before the biotite-quartz aggregate. The presence of a portion of an enstatite crystal suggests that the original mineral was a pyroxene. As, in addition, we may find the biotite-quartz aggregate containing an ilmenite nucleus and scattered fragments of garnet, extending as a circular bight into the side of a hypersthene crystal (Plate IV., fig. 3), there can be little doubt that the hypersthene has taken part in the formation of this aggregate.

The radial arrangement of the small biotite crystals is very noteworthy, and it is so constantly associated with the intergrowth of felspars (Plates IV., fig. 5; V., fig. 4). The intergrowth has normally a fan-shaped arrangement and frequently branches from a biotite flake (Plate XVI., fig. 6), and there can be little doubt that there is a genetic connection. The biotite rosettes often surround an ilmenite nucleus, and, while there is a similarity with an ordinary zone, significance must be attached to the different structure. Though it is difficult to offer definite proof, the whole arrangement suggests the reversal of the biotite-garnet reaction described in No. 947. If we imagine first the formation of the garnet zone around ilmenite as in No. 947 (Plate V., figs. 5 and 6), and then a reversal of the metamorphic conditions to those on the biotite side of the reaction, whereby the garnet disappears and the biotite reappears, we might get the rosetted biotite zones. Such hypothesis provides an intelligible account of the connection between the biotite sprays and the associated myrmikoidal felspar. The evidence of this reversal includes the presence of the garnet fragments in the quartz-biotite zone (Plate IV., fig. 3) which lies between a hypersthene crystal and a large ilmenite surrounded by biotite rosettes. Secondly, a break in the garnet zone around biotite (Plate IV., fig. 3) is found, and the break is marked by a biotite spray which opens out into a myrmikoidal fan which is only visible between crossed nicols, and, therefore, not seen in the photograph. The sprays are also poorly developed on the outside of this garnet rim. The incompleteness of the garnet rim around ilmenite and biotite (Plate VI., fig. 1) may be explained in the same manner.

The felspar in the slide consists of orthoclase, plagioclase (oligoclase andesine), and the myrmikoidal intergrowths. Blebs of quartz may be set in the plagioclase which may be rimmed with the intergrowths (Plate IV., fig. 5). A case has been noticed where the plagioclase is separated from orthoclase, containing abundant minute fusiform inclusions with higher refractive index, by a zone of intergrowths. Large crystals of quartz are irregularly distributed through the slide, in addition to the fine quartz in the biotite aggregates and in the felspar. Pyrite and zircon are accessory.

No. 785 (4).—No. 785 (4) is a second slice cut from the same end of the specimen as No. 783 (2). In many respects this slide is similar to the preceding, but there is a little less hypersthene and garnet. The large crystals of apatite are still prominent, and we have now noticed that the garnet rims may extend on to a crystal of apatite.

The garnet rims extend around the biotite-quartz aggregates in a manner noted in the previous slide. Now the garnet, in addition to the rims, may extend as seams through the aggregate in the same way that has already been seen in the hypersthene. Further, the relic hypersthene in the same aggregates leaves no doubt whatever that the biotite and quartz can be produced in a reaction in which the hypersthene has taken part. For average compositions of these minerals the reaction may be expressed chemically as follows :—

$$\underset{\text{Biotite}}{(KH)_2O,\ 2(FeMg)O,\ Al_2O_3,\ 3SiO_2} + \underset{\text{Quartz}}{5SiO_2} \rightleftarrows \underset{\text{Hypersthene}}{2\{(MgFe)O,\ SiO_2\}} + \underset{\text{Orthoclase}}{K_2O,\ Al_2O_3,\ 6SiO_2}.$$

Excess iron may separate out as iron ore, and K_2O is assumed again to largely dominate over H_2O in the biotite. This reaction has undoubtedly followed the production of the garnet from biotite or pyroxene, and the orthoclase which accompanies the formation of the garnet may react again with the hypersthene.

In one case a biotite crystal, partly crushed, extends into a hypersthene aggregate (Plate IV., fig. 4). Part of the biotite has a garnet rim, and one corner of the biotite area has a perforated appearance with the development of quartz, and is in intimate relation with the biotite. There is only occasional chloritisation of the biotite and serpentinisation of the hypersthene.

No. 785 (3).—The slide No. 785 (3) is cut from the middle of the specimen. The same general features can be recognised here ; but there is less biotite and more hypersthene, most of which is considerably altered to serpentine.

A new feature appears in this slide in a large aggregate of hypersthene and altered hypersthene in which the outlines of the crystals are marked by thin garnet borders (Plate VI., fig. 2). The garnet also penetrates some of the crystals in thin irregular seams. Similar seams have already been noticed in fresh hypersthene and in the garnet-rimmed areas of biotite and quartz. In this aggregate the original hypersthene crystals have assumed a pale-green colour, are slightly pleochroic, and are in part finely fibrous. The least altered still have the polarisation colours of hypersthene, but in many cases the mottled colours of serpentine appear. Strong pleochroic haloes appear in the serpentine. The alteration takes place here through bastite to serpentine.

During the serpentinisation a considerable amount of magnetite (or ilmenite) has separated out ; and this separation is well illustrated in a crystal of partially altered hypersthene, which is apart from the aggregate. The centre of this crystal is still the unaltered pleochroic hypersthene ; but its low polarisation colours indicate that its iron content is small, and that it is passing over into enstatite. The outer portions have changed to clear enstatite or to serpentine, which is brownish in part ; but along the fringe of the crystal there are numerous, small, opaque crystals formed from the liberated iron.

In another crystal the hypersthene has completely changed to enstatite in which serpentinisation has freely developed along the cracks and fractures in a manner common in olivine. This enstatite crystal is seamed irregularly with planes of colourless garnet, and it is certain that the development of the garnet took place prior to the serpentinisation. It probably occurred before the development of the enstatite, because we have previously noted garnet seams in deeply pleochroic hypersthene.

Sometimes these altered crystals of hypersthene contain inclusions of biotite, or of ilmenite surrounded by biotite sprays with associated quartz. But biotite crystals are mostly confined to the margin of the serpentine hypersthene aggregate. These biotites may have the normal garnet rim, produced, no doubt, in the same manner as before by a biotite-plagioclase reaction. Such reaction may explain the garnet fringe around the edge of the aggregate, but it will not reasonably explain the rims and seams in the inner part of the aggregate. The garnet has also been derived in some other manner.

It seems necessary to account for the garnet without any reaction at all, and to assume that the garnet is derived directly from the hypersthene. Holland* has reported the decomposition of augite into garnet and felspar; but there is no reason to suppose that this instance cannot be explained as has been done in the garnet plagioclase pyroxene gneiss (No. 953) of Stillwell Island, in which augite has reacted with labradorite to produce garnet with andesine and quartz. In the same publication Holland refers to the description by Brauns in 1888 of the formation of a lime iron garnet in a palæopicrite by the alteration of augite in which the chemical analysis indicated a removal of Al_2O_3. L. Hezner mentions the record of a pseudomorph of garnet after augite by Pelikan.† These instances, however, are probably not parallel with the present instance.

Van Hise quotes the change of pyrope into enstatite, spinel, and quartz.‡ It is not unlikely that this reaction is reversible, with suitable conditions, and pyrope may be derived from enstatite, provided the suitable amounts of Al_2O_3 are available. If this is so then the type of reaction may be indicated thus—

$$3MgSiO_3 + Al_2O_3 \rightleftarrows Mg_3\,Al_2\,Si_3\,O_{12}$$

The hypersthene that enters into the reaction very probably contains some alumina. According to Dana, hypersthene may contain as much as 10 per cent. of Al_2O_3, and a Victorian example in a titaniferous dacite was found by Richards to contain 4 per cent.§ It can be conceived that the Al_2O_3 content of the hypersthene may provide the alumina in the above reaction, because the amount of serpentinised hypersthene is much greater than the amount of garnet formed. The iron content of the hypersthene may separate out as iron oxide as in the formation of enstatite or enter the garnet molecule. Any content of lime in the hypersthene would also enter the garnet molecule.

As a result of the examination of these four slides we think the most comprehensive name is hypersthene biotite felspar gneiss.

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* T. H. Holland, "Origin and Growth of Garnets," Rec. G.S.I., XXIX., p. 20.

† Op. cit., L. Hezner, p. 67.

‡ "Treatise on Metamorphism," p. 304.

§ "On the Separation and Analysis of Minerals in the Dacite of Mount Dandenong, Victoria," H. C. Richards, Proc Roy. Soc. Vic., vol. XXI., n.s., p. 533.

THE CRYSTALLOBLASTIC ORDER.

It is found difficult in some cases to satisfactorily name the crystalloblastic order. This order contains a list of minerals which have arisen more or less simultaneously during its recrystallisation. If all the minerals in the rock have not formed at the same period, then they cannot be placed in a single crystalloblastic order, and it frequently happens that a rock carries traces of two metamorphic phases—each characterised by certain minerals. Sometimes two minerals in a rock may not come in contact, and their relative position in the order cannot be fixed. In some cases, as at Madigan Nunatak, the contacts may be wholly or partially replaced by areas of pulverised material.

In the garnet cordierite gneiss, garnet and sillimanite crystals have not been observed in contact, and are bracketed in the crystalloblastic, which appears to be as follows :—Garnet, sillimanite, ilmenite, biotite, felspar, cordierite, quartz.

In the cyanite felspar gneiss from Garnet Point the cyanite exerts its form against the biotite and must, therefore, be placed above the biotite in the sequence. In this case the cyanite cannot be compared with the garnet or cordierite, as these are looked upon as secondary relics from the kata zone metamorphism.

In the hypersthene alkali felspar gneiss, No. 949 (charnockite), the observed order is—Apatite, ilmenite ; hypersthene ; biotite ; felspar ; quartz.

In the less acid, hypersthene felspar gneisses, containing garnet, the garnet is subsequent to the formation of most of the biotite, and is, therefore, omitted from the sequence, which appears to be—Apatite, ilmenite ; pyroxene ; biotite ; felspar ; quartz.

SUMMARY.

Garnet gneisses are obtained from Cape Gray, Garnet Point, and the Cape Pigeon Rocks—three rocky outcrops on the present shore line that are accessible to a sledging party on the mainland. A fourth locality is Stillwell Island, distant nearly two miles from the shore line, and was visited by the ship's boat.

The gneisses may be summarised thus—

Cape Gray	Garnet cordierite gneiss.
Garnet Point.................	Cyanite biotite gneiss.
	Garnet felspar gneiss.
Stillwell Island	Garnet felspar gneiss.
	Hypersthene felspar gneisses.
Cape Pigeon Rocks	Garnet gneiss.
	Hypersthene biotite felspar gneiss.

The garnet felspar gneisses on Garnet Point and Stillwell Island are light coloured and mottled by large aggregates of garnet and biotite, which are more or less spherical in shape and up to 2in. in diameter. These aggregates represent original and complete crystals of garnet. Cordierite and sillimanite are most prominent at Cape Gray, but are found at the other localities, where they are interpreted as secondary relics. With the recession of garnet and cordierite, biotite with quartz and felspar become prominent. Biotite and quartz have been produced by the reaction of garnet and felspar. The biotite so produced is a pale green variety which develops later into the normal brown biotite. The alteration from the green to the brown colour may be effected by the radio-active rays which produce the pleochroic haloes in the biotite.

The junction between the cyanite biotite gneiss and an amphibolite dyke has been described at Garnet Point. Near the junction there is considerable garnet and cyanite in the gneiss. The cyanite is not normal and shows prominent lamellar twinning, but its double refraction is estimated to be about 0·019—a value higher than recorded values for cyanite. There is perfect crystalline continuity across the junction, which is only indefinitely marked by the gradual appearance of hornblende in the section. The cyanite and quartz travel further into the amphibolite than the garnet or biotite, and the cyanite has been noticed in the amphibolite at a distance of 1in. from the apparent junction. The cyanite may be intergrown with the hornblende in the amphibolite. It is not considered possible to explain these features by assimilation of the sedimentary rock by the igneous rock prior to the metamorphism. The characters of the complex of sediment and dyke are solely due to the recrystallisation, during which it is supposed that a limited migration of material occurred across the pre-existing junction, tending to efface it. It is viewed as another example of metamorphic diffusion.

The chemical composition, as well as the mineral composition, shows that these gneisses are sedimentary in origin.

The gneisses in each case are placed among the Aluminium Silicate Gneisses in Grubenmann's classification of the crystalline schists. The rock at Cape Gray, the most northerly outcrop, is placed in the family of the cordierite gneiss in the kata division. Kata zone metamorphism is found in each of the other outcrops but is modified first by meso zone metamorphism and, later, by additional traces of epi zone metamorphism. At Madigan Nunatak, situated on the ridge which terminates in Cape Gray and 18½ miles due south of it, we have already described the rocks as examples of kata zone metamorphism modified by strong epi zone features. We now find that, of these four localities, the nearest in point of distance from the Madigan Nunatak is the locality in which traces of epi zone metamorphism have been described as superimposed upon kata zone metamorphism. Cape Gray, the furthest in point of distance from the Madigan Nunatak, possesses the least modified kata zone metamorphism. The intermediate localities possess kata zone metamorphism modified by meso zone metamorphism to a degree sufficient to place the rocks in meso division of the schist group. In the latter case the specific families of cyanite gneiss and meso garnet gneiss are represented.

In addition to the garnet felspar gneiss on Stillwell Island, acid hypersthenic gneisses occur. The only specimen of gneiss, apart from the altered dykes, collected from the

Cape Pigeon Rocks, is also a hypersthene gneiss. It is also probable that similar rocks occur at Garnet Point. These rocks are related to the acid hypersthenic gneisses of Madigan Nunatak and Aurora Peak. One example from the summit of the island is found in dyke form, and is no doubt of igneous origin. This rock is a granulitic aggregate of quartz, orthoclase, plagioclase, and hypersthene. Biotite and ilmenite are developed by the reaction of the hypersthene with the felspar. The hypersthene also changes to a greenish serpentinous mineral, as in the rocks at Madigan Nunatak and Aurora Peak. The rock is identical in kind with the normal charnockite of the Indian charnockite series.

Two other examples of hypersthene alkali felspar gneisses are described from Stillwell Island and are distinguished from the first by a higher specific gravity and by the coarse-grained character in the hand specimen. In one of these there is considerable quartz, but only fragmentary garnet, and the brown biotite is found developing through the stage of pale-green biotite. The hypersthene may lose its iron content and change into enstatite. In the second considerable garnet is found in part, but very little quartz. The quartz in the first is replaced by orthoclase in the second. The garnet appears not only as large crystals but also as granular zones surrounding ilmenite, biotite, and hypersthene. As zones of biotite may surround ilmenite and hypersthene, these garnet rims may be explained in each case by a reaction between biotite and plagioclase and quartz, producing garnet and orthoclase. This reaction is found to be highly localised, being absent from a second section cut at the other end of the specimen, and distant 3in. from the first section. A third section cut from the middle of the same specimen shows some garnet. The garnet-forming conditions are, therefore, very limited.

Remarkable variation of a similar kind is found in the specimen of hypersthenic gneiss from the Cape Pigeon Rocks. The specimen was not more than 3½in. long before the slicing, and four sections have been studied. In the first of these there is very little garnet and no hypersthene. At the other end of the specimen there is considerable hypersthene and the garnet rims are equally developed as in the preceding example from Stillwell Island. Here, in addition to the ilmenite, biotite, and hypersthene nuclei, we find the garnet rims enclosing curious areas of small biotites and quartz. These areas are looked upon as formed by the reaction of hypersthene with orthoclase. In another case the garnet penetrates the hypersthene crystals in the form of thin seams. In the fourth there is a curious aggregate of hypersthene and altered hypersthene in which the outlines of the crystals are marked by garnet borders. The garnet rims are in most cases explained, as at Stillwell Island, by a reaction between biotite, plagioclase and quartz; but in the hypersthene aggregate, it is supposed that the hypersthene, containing some Al_2O_3, changes in part into garnet.

A very noticeable feature in this type of rock is the presence of biotite both in the form of platy crystals and in fan-shaped sprays. The fan-shaped sprays of biotite are constantly associated with an intergrowth of felspars, and a genetic connection is assumed between them. It is considered likely that these biotite fans are produced from garnet by a reversal of the biotite-plagioclase-quartz reaction.

The specific gravity of these hypersthenic gneisses of varying content ranges between 2·74 and 2·76, and are comparable with the intermediate members of the Indian charnockite series. They resemble the intermediate charnockites in the irregular distribution of the ferromagnesian silicates and in the prominence of the felspar intergrowths and inclusions. The Antarctic specimens differ from the Indian rocks in the possession of the well-defined garnet rims.

The primary igneous origin of these intermediate types is determined by analogy with the normal charnockite-like rocks, though the occurrence at the Cape Pigeon Rocks is probably that of an original dyke.

CHAPTER XI.

THE CAPE GRAY METAMORPHOSED DYKE SERIES.

In each exposure on the Cape Gray Promontory basic dykes are found traversing the garnet gneisses. Photographs were obtained from the localities visited by the sledging party from the mainland, and these show the obvious dyke characters (Plate XXVI., fig. 4; Plate XXVII., figs. 1, 2, 4).

Each locality will be dealt with separately, as each possesses different metamorphic features.

Cape Gray.

At Cape Gray a perfect network of dykes is visible on the bare rock floor. A diagrammatic sketch of this network is given in Fig. 13. The dykes branched and junctioned frequently and small tongues could be seen running from the dyke channel out into the gneiss (Plate XXVII., fig. 2). In places they enclose large fragments of gneiss. So perfectly preserved is the network, we immediately assumed that the dyke series would be much younger than the development of the gneiss. Examination,

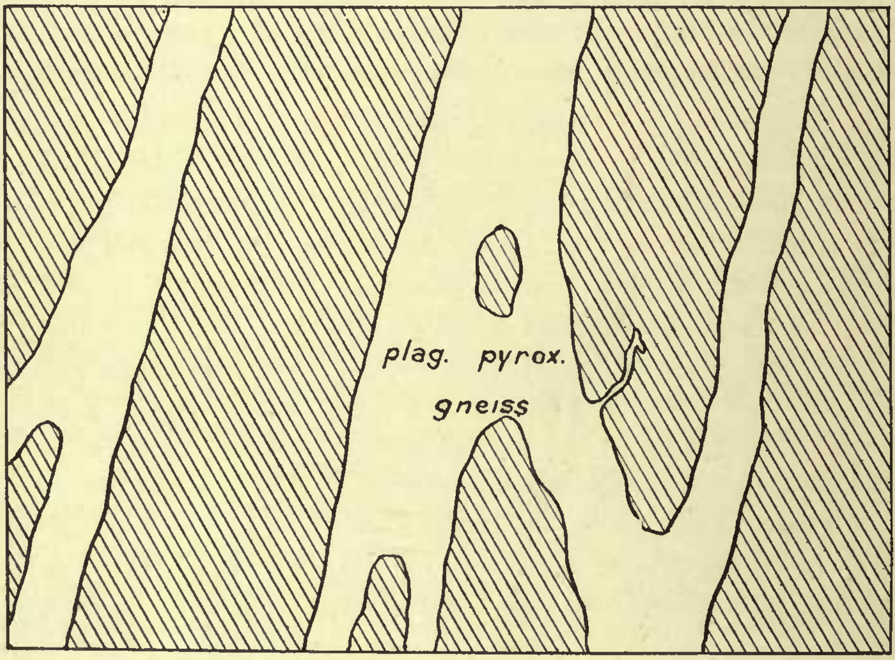

Fig. 13.

Diagrammatic Sketch of the Relation of the Garnet Cordierite Gneiss to the Plagioclase Pyroxene Gneiss at the West End of Cape Gray.

The shaded area represents the garnet cordierite gneiss.

however, shows that foliation can be traced in part of the dykes. Most of the dyke specimens look like dense fine-grained basalt, except that a vitreous appearance is more noticeable on the fractured surface. Microscopic examination shows that they are not normal igneous rocks, and we find a definite metamorphism of a varying kind.

No. 773.—No. 773 is an example of the massive rock. The structure is finely granoblastic and relic structures can be seen. The outlines of the felspar laths of the primary dolerite are plainly visible (Plate VI., fig. 5), and are marked by lines of granular augite producing a blastophitic structure. Diablastic structure is produced by an intergrowth of augite and felspar. The mineral composition is as follows :—

Felspar	40·5
Pyroxene	45·3
Hornblende	3·4
Ilmenite	6·6
Biotite	4·2

The original felspar laths are replaced by a granoblastic aggregate of clear secondary felspar, which becomes evident in polarised light (Plate VI., fig. 6). The average absolute grain size of the aggregates is 0·05mm. In some places relic felspar is found ; it is always dusty with minute inclusions, and, therefore, appears in contrast to the clear secondary felspar. The relic felspar is both simple twinned and lamellar twinned, and an extinction angle of 29° has been measured from the trace of the lamellæ. This felspar is, therefore, labradorite. The relic felspar is usually surrounded by a zone of granular clear felspar, which may contain vermicular grains of pyroxene. The refractive index of the secondary felspar is less than that of the labradorite, but the difference is not great as it is not noticeable under low power objectives. The maximum extinction angle obtained in pieces showing twinning is 18°, and hence we consider it to be an andesine. The pyroxene forms 45·3 per cent. of the rock and includes hypersthene and augite and relic augite. The relic augite is dusty through numerous minute inclusions of ilmenite. These inclusions are more or less regularly arranged and may be called schiller inclusions. Plates of this dusty augite have been found which have been ophitically inlaid with laths of relic felspar, now represented by strings of secondary felspar. The recrystallisation of the primary dusty augite has produced a granular aggregate of clear secondary pyroxene, while the minute dusty inclusions have coalesced and now form a number of small ilmenite crystals. The clear granular pyroxene sometimes forms a zone around the dusty augite, but it may appear as a parasitic aggregate enclosed within the primary dusty plate. Some of this granular pyroxene is certainly hypersthene with its pink to green pleochroism and its straight extinction ; but it is impossible to determine its proportions to the secondary augite.

The development of the secondary augite and hypersthene from the primary augite means that the secondary augite will be more aluminous than the primary augite. A high value for alumina in this secondary augite provides a point of resemblance to the omphacite in the Otz Valley* eclogites. The development of the secondary pyroxene involves a change in the double refraction and many augite crystals show uneven polarisation colours. If the primary augite is showing blues and greenish blues of the second order, the recrystallised augite may show the higher greens; but, on the other hand, the degree of colour is often lowered to the reddish purples and violet at the top of the first order. In the latter, grains of hypersthene have been seen as a nucleus. No corresponding change in the extinction angles of the augites has been noted.

A second type of alteration of augite that can be traced in this rock is the passage into green pleochroic hornblende. The 3·4 per cent. hornblende in this rock has developed in this way. The hornblende grains possess the same average size as the secondary augite or felspar, but their distribution is not uniform. It is found in sporadic patches which sometimes seem to indicate the outline of a prismatic crystal of pyroxene. The 4·2 per cent. of secondary brown biotite is distributed more uniformly throughout the rock, and some of it may be relic. Ilmenite abounds in small crystals and as minute inclusions in the augite. It is definitely recognised as some of the larger crystals show alteration to greyish leucoxene. Occasional grains of pyrite are also present.

The metamorphic character of this rock certainly dominates the igneous character, and, therefore, we call the rock a plagioclase pyroxene gneiss.

No. 766.—This example is a modified variety of No. 773, and shows distinct schistosity. The secondary felspar and the secondary pyroxene are arranged approximately in layers, producing a crystallisation schistosity. It is possible that the original rock had a coarser grain size than the original rock of No. 773, because the plates of relic augite are much larger in this example. The average grain size of the recrystallised individuals is about twice as large. Relic dusty felspar is still present, and is surrounded by a granulitic mass of clear felspar. In one case sharp lamellar twinning is present, and the lamellæ have extinction angles of 36° and 37°, again indicating labradorite. The recrystallisation of the primary pyroxene is more diagrammatic than in No. 773. Plates of primary augite may form the nucleus of beautiful granoblastic zones of clear secondary pyroxene whose growth in the direction of the schistosity may produce long tails (Plate VII., fig. 1). Many of the grains can be identified as hypersthene; in many cases where the primary augite is completely replaced, the layer of granular pyroxene may enclose areas, sometimes circular, of fine vermicoidal pyroxene set in an aggregate of felspar producing a diablastic structure. At other times the vermicular pyroxene forms a fringe around the outline of a primary pyroxene in the same manner as is more prominently exhibited in No. 951 from Stillwell Island. This diablastic pyroxene has character different from the granular pyroxene, and is not unlike the intermediate stage in the formation of garnet which is seen in the Stillwell Island rocks. The suggestion, therefore, is that these are incipient garnet areas.

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* The Percentage of Alumina in the Omphacite in the Otz Valley Eclogite is 10·91 per cent. "Beitrag zur Kenntnis der Eklogite und Amphibolite," Laura Hezner. Wein, 1903, p. 10.

Apart from the schistose character the important difference from No. 773 is the large percentage of hornblende. The grain size of the hornblende tends to be a little larger than that of the secondary pyroxene. The green hornblende is found developing directly from the relic platy augite and from the secondary pyroxene. Hornblende grains are found indiscriminately associated with the granular pyroxene, and they border plates of primary augite and arise parasitically within them. Further, hornblende with small crystals of ilmenite, completely replaces the pyroxene in some of the crystalline layers of the rock. Biotite is much less important in this rock and shows a very strong tendency to be confined to the pyroxene areas.

The percentage mineral composition of this section is—

Felspar	33·6
Pyroxene	24·4
Hornblende	39·5
Ilmenite	2·3
Biotite	0·2
Apatite	Present

This composition cannot be directly compared with No. 773, because it is a schistose rock, and because the section has been cut at about 30° to the plane of schistosity instead of 90°. The difference in the ratio of the felspar to the ferromagnesian cannot be considered to demonstrate a change in chemical composition. The expression is, however, useful to demonstrate the degree of hornblendisation. There is far too much pyroxene for the rock to be considered an amphibolite. It is a transition type between the plagioclase pyroxene gneiss (No. 773) and an amphibolite, and should, therefore, be called a hornblende plagioclase pyroxene gneiss.

Stillwell Island.

The basic rocks observed by Sir Douglas Mawson on Stillwell Island were considered by him in the field to be altered dykes. "Irregular bands of black rock," he says in his diary, "exist as at Cape Denison: some of these are not much altered, others are full of fine garnet. The black bands usually extend long distances, and all have the appearance of original dykes. A vertical section of one, exposed in a cliff face, showed that it dipped regularly at 45° to the west." The island contains some of the most interesting members of this dyke series, and remarkable stages of incipient alteration are found.

No. 951.—This example has a coarser grain than most members of the dyke series. The grain size is sufficient to suggest a primary gabbro, because there is little alteration. On the other hand the rock may be a completely recrystallised example, and the "little alteration" may be the incipient development of a second metamorphic phase. The latter interpretation is rather supported by the granulitic texture and the recrystallised character of the surrounding rocks. In section the rock consists of felspar, augite.

ite, ilmenite, and apatite.

The bulk of the felspar is in clear transparent crystals in which the twinning is sometimes indefinite and irregular. A maximum extinction angle of 28° has been measured, and the felspar is, therefore, interpreted as labradorite. Both augite and hypersthene are present and are free from the dusty inclusions of ilmenite. Brown biotite is present both in large platy crystals and in small secondary crystals. The ilmenite is abundant.

The large pyroxene and biotite crystals, as well as the ilmenite, are almost invariably bordered by a zone which follows the outline of the crystal, no matter how irregular and ragged it may be (Plate VII., fig. 5). The zone may be described as a diablastic intergrowth of vermicular pyroxene and felspar; but the pyroxene is different from the normal pyroxene, and the felspar is not the relic labradorite. The vermicoidal pyroxene has a lighter colour than the normal pyroxene, suggesting that part of the iron may have separated out to form ilmenite. The felspar is a more sodic felspar and its development from the calcic felspar is very noticeable. Sometimes small secondary biotites are seen in these diablastic fringes, as well as small ilmenites. Ilmenite crystals, large or small, are always associated with the pyroxenic parts of the slide though there is no direct evidence to show here, as in No. 773, that they form during the recrystallisation by the coalescence of minute inclusions in the primary pyroxene. The same diablastic fringe is also found surrounding large ilmenite and biotite crystals; but it does not accompany these with the same regularity as it accompanies the pyroxene. Ilmenite crystals may be found with a rim of pyroxene, and if this rim should pass into the vermicoidal type we should get the ilmenite crystal surrounded by the diablastic zone in the way we have often observed in this section. Some of the iron ore has the appearance of pyrrhotite.

There can be no doubt that this diablastic zone is a product of a reaction between labradorite and pyroxene, or between labradorite and biotite. Stages may be observed between augites surrounded by a thin rim and small augites surrounded by a thick zone. In the latter the remaining augite is mouse eaten and has nearly disappeared.

The formation of biotite in the vermicoidal zone must be associated first with a supply of K_2O from the felspar, and secondly with the temperature factor during metamorphism. The temperature factor must be high to permit the formation of secondary pyroxene, and it may have been, in the first stage of metamorphism, too high for biotite. Biotite may have been formed only after a lowering of the temperature, and the appearance of the biotite is quite in agreement with the suggestion that the biotite is subsequent to the initial formation of the rim. A study of the phenomena in No. 935 shows that this reaction is the initial stage in the formation of garnet.

The rock may be described as a plagioclase pyroxene gneiss, which shows the incipient stages of garnet formation.

No. 942.—No. 942 is another example which still retains normal igneous structures. It occurs in dyke-like bands, up to 10ft. wide, crossing the garnet gneiss. It is a much finer grained type than No. 951, and, in the hand specimen, might be taken for a slightly altered dolerite, because there seem to be fine-grained portions, representing the unaltered dolerite, surrounded by more coarsely crystalline rock, representing the altered part. No part, however, is found to be unaltered in section.

In this section we find that the outlines of primary felspar and pyroxene of the dolerite have quite disappeared. The former crystals are now replaced by a finely diablastic aggregate of pyroxene and felspar. The individuals in the aggregates are more granular in contrast to the vermicoidal appearance in the preceding. The aggregates may contain small garnets and biotites with numerous small crystals of ilmenite ; a little quartz has been detected and is probably associated with the formation of garnet. We call these aggregates diablastic, because we consider them to be produced in the decrystallisation, or breaking down, of the primary pyroxene and labradorite which results partly in the secondary pyroxene and a more sodic plagioclase. This decrystallisation is followed by a recrystallisation, and we find here and there granulitic aggregates of secondary pyroxene, including both orthorhombic and monoclinic forms, identical in kind with those produced in the Cape Gray rocks.

The recrystallisation or the building of large crystals from smaller ones seems to have taken place under conditions in this case which have favored the formation of green hornblende and biotite. Hornblende and biotite possess an average grain size much greater than the pyroxene, and are both much more abundant than in No. 951. The large crystals of hornblende and biotite are frequently aggregated in clusters, just as if each cluster were a metamorphic differentiation centre of hornblende or biotite. Hornblende and biotite are frequently intergrown, indicating that they have formed at the same time. Often the hornblende clusters have a linear trend, and sometimes they are circular, enclosing areas of the diablastic felspar and pyroxene (Plate VII., fig. 6). In doing this, they provide the initial stages of the growth of the phenomena to be described in No. 953.

Hypersthene is again noted among the pyroxene, and apatite and odd grains of calcite are present.

The metamorphic character of this example dominates the igneous, and most of the rock has suffered complete decrystallisation. It may be called a hornblende plagioclase pyroxene gneiss.

No. 952.—In some instances the hornblendisation noted in the preceding has proceeded to such an extent that a normal amphibolite has formed. No. 952 is an example of this type, obtained from among the basic plagioclase augite rocks of Stillwell Island.

In the hand specimen this rock is similar to the fine grained, massive varieties at Cape Denison. In section, it consists chiefly of hornblende and felspar (labradorite-andesine), with small amounts of ilmenite, biotite, and garnet. Sphene, calcite, and apatite have been detected.

A small portion of the hornblende is very pale in colour, and has the appearance of uralite rather than that of the normal green hornblende. The uralite has green spots of normal hornblende, and the cleavage passes indiscriminately through both. The uralite is evidently passing into hornblende, or *vice versa.* Sometimes there are bluish glaucophane borders on the hornblende crystals.

The biotite is intergrown with the hornblende as before. There are occasional small blebs of garnet usually set in the felspar. Similar in outline and situation are occasional small blebs of calcite, and these are probably the remains of former garnet from which the Al_2O_3 and the SiO_2 have been withdrawn, and the excess lime has been converted by carbonation into calcite. Small dusty ilmenite areas have been found, and suggest that some of the ilmenite has formed by the aggregation of this dust.

The rock is a true amphibolite, which has formed under meso zone conditions, and its presence is noteworthy among a large number of recrystallised basic rocks in which garnet and pyroxene predominate.

No. 935.—This specimen was obtained from a broad band about 20ft. wide with ill-defined boundaries. The rock is dark coloured and massive, with a vitreous lustre, but without any suggestion of schistose texture in the hand specimen. The doleritic character is suggested by the presence of felspar laths and large black augites, which can be seen with the naked eye. With the aid of a pocket lens small garnets are found to be numerous.

In thin section we find abundant garnet, pyroxene, hornblende, ilmenite, and felspar. Pyrite and apatite are also found. The mineral proportions in slide No. 935 (2) have been determined as follows :—

Felspar	25·4
Pyroxene	21·3
Hornblende	25·3
Garnet	15·9
Ilmenite	5·7
Biotite	6·0
Apatite	0·4

The transformation of augite and its reactions with the felspar are very plain. There are large plates of augite crowded with the minute dusty ilmenite inclusions which we know are a relic of the pre-existing dolerite. We can trace the following changes in this primary augite :—

(1) There are parasitic clumps of small, interlocking, granular pyroxene crystals which are clear and have been formed in the recrystallisation of the dusty pyroxene. The primary schiller inclusions have been thrown out, and have coalesced to form large ilmenite crystals. This is the same change as was observed in No. 773 from Cape Gray. Partial aggregations of the minute ilmenite dust are often seen (Plate VII., fig. 2).

(2) There are seams and patches of granular green hornblende in cracks and fractures of the relic pyroxene, and among the aggregates of secondary granular pyroxene. It appears that the hornblende has formed directly from both the relic dusty augite and from the secondary pyroxene. A large plate of relic augite may enclose parasitically a granular aggregate of green hornblende crystals in which an ilmenite crystal may be set as a nucleus, formed, as before, by the coalescence of the primary ilmenite inclusions. Sometimes larger hornblende crystals have grown out of the aggregates of small granular hornblende.

(3) There is frequently a considerable amount of small secondary biotite associated with the granular hornblende so intimately that there can be no doubt they have arisen at the same time as the hornblende. Its formation depends on the chemical supply of potash and water.

(4) The large relic augites, which may be replaced by secondary pyroxene or hornblende, are bordered by a zone of small garnets which may be partly idioblastic (Plate VIII., figs. 4 and 5). Between the edge of the pyroxene crystal and the garnet rim there is usually a thin zone of clear felspar (or quartz). The manner in which the garnet rim follows the outline of the relic pyroxene can be easily seen when the section is observed with a low power lens. The character of the felspar in the neighbourhood of the garnet undergoes an obvious change when observed in polarised light (Plate VIII., fig. 6). The formation of the garnet absorbs lime from the primary labradorite, and we may find a labradorite crystal zoned with a rim of more sodic felspar. By analogy with phenomena in metallic alloys, the manner of extraction of the anorthite from the solid solution of plagioclase is strongly suggestive of solid diffusion. The reaction that has taken place is one that has been quoted by Grubenmann,[*] and may be written in this case—

$$\begin{array}{ccccccc} \text{Augite} & & \text{Labradorite} & & \text{Garnet} & & \text{Andesine} \\ CaMgSi_2O_6 & + & 2CaAl_2Si_2O_8,\ NaAlSi_3O_8 & \rightleftharpoons & Ca_2MgAl_2Si_3O_{12} & + & CaAl_2Si_2O_8,\ NaAlSi_3O_8 \\ & & & & \text{Quartz} & & \\ & & & & +\ SiO_2 & & \end{array}$$

There is no evidence to lead us to ascribe these compositions to augite, felspar, and garnet, but, by doing so, we can more readily understand how the garnet is formed and the more sodic plagioclase produced. More augite may combine with another anorthite molecule of the andesine, and a still more sodic plagioclase produced. The separation of the quartz has been definitely noted in a second section No. 935 (2) from the same specimen, and that it does appear with garnet is abundantly evident in No. 953.

Sometimes where a blastophitic structure can be recognised in No. 935 (2), and a relic labradorite crystal crosses a plate of dusty augite, we may find no garnet border. Along the edge of the felspar there are numerous small rounded inclusions like incipient garnets, and the part of felspar near the contact with augite is more sodic than the central portion. The relic augite is bordered by the secondary hornblende and this may have prevented the interaction along this junction.

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[*] "Die Kristallinen Schiefer, vol. I., p. 34."

The proportions of the minerals—garnet, biotite, and hornblende—vary in different slides with the varying amounts of recrystallisation.

If these varying alterations had not occurred the rock would consist chiefly of augite, labradorite, and ilmenite, and, perhaps, some biotite. The primary ophitic structure has been detected, and there can be no doubt at all that the rock is a metamorphosed dolerite. Yet it has been reported as a band with ill-defined boundaries. Such ill-defined borders are probably to be explained by some such process as metamorphic diffusion. The formation of the garnet in this case is most certainly not due to any absorption of any sedimentary material, as has been suggested by Cole for the origin of certain garnet amphibolites in Ireland.*

The rock may be called a garnet plagioclase pyroxene gneiss.

No. 953.—Several specimens of a garnet amphibolite have been collected from Stillwell Island, where a dark basic band becomes definitely banded. Specimen No. 953 is a moderately coarse-grained rock with noticeable schistosity showing pink garnet, black hornblende, and biotite.

In section, the rock is remarkable for its percentage of hornblende, garnet, and quartz ; and a casual study would suggest that the rock possesses a composition different from that of the more obvious dyke rocks. The chemical analysis shows that this is not so. The percentage mineral composition has been determined as follows :—

Felspar and quartz	24·1
Pyroxene	2·4
Hornblende	38·7
Garnet	19·7
Ilmenite	6·7
Biotite	7·9
Apatite and sphene	0·5

The green hornblende is the most abundant constituent, and at times seems to be wrapped round a garnet crystal in the manner suggested in No. 942. The grains are much embayed and sometimes poikiloblastic. The pink garnet is often crowded with small inclusions. The grains are mostly rounded, but exert their form against the felspar and quartz, and tend to do so against the hornblende. While quartz forms the bulk of the colourless constituents, a garnet crystal is always set in a felspar base—an association which clearly has genetic meaning. A twinned felspar has been found to give an extinction angle of 33° measured from the lamellæ, and to possess a refractive index above quartz. This is labradorite, but I think the bulk of the felspar has a refractive index below quartz and a small extinction angle. There is a little pyroxene present, but there are still good examples of the pyroxene-felspar vermicoidal intergrowths. These intergrowths may extend as a bite into a garnet crystal, but it may be interpreted either as a breaking down of the garnet or as a patch of unformed garnet (Plate VIII., fig. 1). It may form a zone around ilmenite crystals in the manner suggested in No. 935; and as the ilmenite crystal may be embedded in garnet, the pyroxene-felspar interlacing may form an annulus between the ilmenite and the garnet (Plate VIII., figs. 2 and 3). The pyroxene " fingers " are often radial, both to an ilmenite nucleus and to a garnet nucleus, and then a " centric structure " is formed. The hornblende has developed from the pyroxene, and we sometimes find the normal pyroxene " fingers " of the intergrowth converted into spokes of hornblende; more rarely we find spokes of biotite. Sometimes we find the intergrowth embedded in a crystal of hornblende.

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* "On the Growth of Crystals in the Contact Zone of Granite and Amphibolite," G. A. J. Cole, Proc. Roy. Irish Acad., vol. 25, sect. B, 1905, p. 117.

A large individual of ilmenite is often a network rather than a compact mass, and this is due to the imperfect coalescence of the small primary ilmenite crystals. Occasionally the ilmenite network is set in a pyroxene base, and this is clear evidence that it is due to the aggregation of minute inclusions in the primary augite, in the same way as was observed in several sections. In all cases here this pyroxene-felspar intergrowth, which we have included as a diablastic structure, may be explained on the hypothesis of the interaction between pyroxene and anorthite to produce garnet and quartz. This reaction is, doubtless, reversible. It has proceeded in the direction of the garnet in this example; but there is no reason why it should not proceed in the reverse direction in certain examples in which garnet is said to be disappearing.* The abundant quartz accompanying the abundant garnet is clear evidence that SiO_2 is separated in the reaction.

The size of the garnet crystals is large in comparison with that of the garnet crystals which form the garnet rims in No. 935. This can be readily explained as being due to the growth of larger garnets at the expense of smaller crystals, a phenomenon which has been exemplified by the hornblende in the Cape Denison series, and which will subsequently be exemplified by the pyroxene in this series.

The rock is described as a garnet amphibolite. The felspar of the normal amphibolite is here partly replaced by garnet.

Cape Pigeon Rocks.

Several dykes of basic rock exist on this locality. The obvious nature of the dykes is recorded in photographs. Two large dykes (Plate XXVII., figs. 1 and 4) cut obliquely across the foliation and are upwards of 30ft. wide. There are numerous smaller ones as well (Plate XXVI., fig. 4), and some are only 3in. wide.

No. 767.—Specimen No. 767 is an example of the large dyke. It is a dark, fine-grained rock in which a faint schistosity may be detected. The schistosity is recognisable in the slide, and there has been complete recrystallisation of the primary dolerite.

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* " Untersuchungen die Altkristallinischen Schiefergesteine," Lehmann, Bonn, 1884, Tafel XXIV., fig. 6.

The Rosiwal analyses of two slides gave the following results:—

	I.		II.
Felspar	45·3	....	38·2
Pyroxene	25·8	....	26·7
Hornblende	19·1	....	24·1
Garnet	3·2	....	2·9
Iron ore	4·3	....	4·9
Biotite	2·1	....	2·9
Sphene, apatite	0·2	....	0·3

The first of these is cut parallel to the schistosity, and its higher felspar percentage is due to the fact that the schistosity is marked by strings of felspar in the hand specimen. The second slide is cut in a haphazard direction, and the measurement is made to determine the variation in the garnet percentage. This variation proves to be less than anticipated.

The rock has a finely granoblastic structure. The felspar consists of water-clear grains which sometimes show diablastic structure. The pyroxene, which occupies one-quarter of the rock volume, includes plates of relic, dusty augite; but it mostly forms small granular crystals of augite and hypersthene, aggregated in areas which originally represent large primary augite crystals. The clear recrystallised augite has a pale green colour as before, and is practically free from the ilmenite inclusions. The more pleochroic hypersthene is again present among the recrystallised pyroxene. The percentage of green hornblende is not much less than that of the pyroxene, and indicates the prominent degree of hornblendisation of the pyroxene. The garnet appears in small pink crystals and is usually set in felspar areas; this can be taken as evidence that it has formed in the same way as in the basic rocks of Stillwell Island. The brown biotite is usually associated with the pyroxene and hornblende areas.

An interesting feature in this rock is the presence of a shear line which cuts across the schistosity. This line is marked chiefly by a decolouration of the hornblende and by broken strings of pyrite. The hornblende may assume a pale green colour, and, if the bright polarisation are absent, it may look like chlorite. Sometimes the shear line may cut straight a crystal of green hornblende and then there appears a belt of colourless hornblende in the green crystal, and this belt is even more noticeable in polarised light. Sometimes there is a pale green mineral with high polarisation colours in the shear zone, and as it has straight extinction it is looked upon as a pale biotite. In addition, there is a very fine granular aggregate of highly polarising mineral, which is possibly talc. The felspar becomes saussuritised and, in general, there is a fuzziness in the neighbourhood of the line. Conditions along a shear plane would correspond in some measure with the conditions of the epi zone of metamorphism; and the pale hornblende, the chlorite, the talc, and the saussurite are, in general, looked upon as epi zone products.

The rock may be called a hornblende plagioclase pyroxene gneiss. It is similar to the plagioclase pyroxene gneisses of Cape Gray, and in its garnet content it shows affinities with the garnet plagioclase pyroxene gneiss (No. 935) and with the garnet amphibolite (No. 953).

No. 782.—Specimen No. 782 was collected from one of the narrower dykes at the Cape Pigeon Rocks. It is a dark, fine-grained rock with abundant glistening hornblende.

In section, the rock is found to be quite different in general appearance from No. 767, a fact which is eloquently expressed by the following mineral composition :—

Hornblende	49·0
Felspar	31·8
Pyroxene	7·6
Iron ore	7·5
Biotite	3·7
Apatite	0·4

The increased amount of hornblende and the decreased amount of pyroxene is the most important difference ; and it is now noticed that the mineral composition approximates to that of the Cape Denison amphibolites. If all the pyroxene had disappeared the proportion of hornblende to felspar would be the same as in some members of that series.

The green hornblende is thus the most abundant mineral in this slide. The hornblende crystals, together with the more rare crystals of brown biotite, show a more or less parallel arrangement, indicating the schistose nature of the rock. Very rarely a colourless hornblende is intergrown with the green hornblende, similar to part of that seen in the shear zone in No. 767. Both hypersthene and augite can be found among the relic pyroxene distributed in patchy areas throughout the slide. It is often in fragmentary form, and the fragments which are set in felspar can be determined by polarised light to have been parts of a large crystal showing poikiloblastic structure. Part of the relic pyroxene is altered to a greenish-brown micaceous product. The felspar is again perfectly clear and ilmenite is abundant as usual. Pyrite is present.

The presence of the pyroxene makes the relation of this specimen to the hornblende plagioclase pyroxene gneiss No. 767 obvious, and the primary types must have been very similar. The differences are due to varying conditions during metamorphism. The pyroxene felspar areas also suggest a likeness to the type No. 942 from Stillwell Island, in which hornblende is not so abundant but the pyroxene areas more prominent. The rock may be called an augite amphibolite.

No. 771.—A closely related type to No. 782 is No. 771. This specimen has a much finer grain and is less schistose.

It consists of a fine granoblastic mass of hornblende and felspar, with insignificant amounts of biotite and ilmenite, but the latter may be surrounded by sphene. There are occasional large crystals of saussuritised felspar and neither pyroxene nor garnet is present. The rock is a typical amphibolite.

A shear zone, developed subsequently to the formation of the hornblende, can be detected in this rock as in No. 767. Without the microscope the shear plane looks like a thin vein running through the slide. Under the microscope it is again marked by a line of decolourised hornblende, saussuritised felspar, and some fine, highly polarising aggregates. The broken strings of pyrite do not appear in this case, but specks of this mineral are found in this zone.

These specimens of amphibolite, Nos. 782 and 771, were collected from the narrow dykes on the Cape Pigeon Rocks, whereas the very broad dyke produces a hornblende plagioclase pyroxene gneiss. We have insufficient data to determine whether this is generally the case. It may be so, and it is quite possible that thin dyke sheets may tend to become shear planes during the compression of a composite rock body, in which case the thin dykes may be subjected to metamorphic conditions of the meso or epi zone rather than those of the kata zone.

No. 786.—Specimen No. 786 was collected as an amphibolite associated with the gneiss. It did not appear in the field as a definite dyke-like band. It is much coarser grained than the other amphibolites, and felspar and hornblende are plainly visible in the hand specimen.

Under the microscope, however, it is found to be similar in kind to the altered dyke rocks. The same type of green hornblende is again the most abundant mineral and its development from the pale green pyroxene is apparent. The hornblende sometimes contains inclusions of sphene. Both quartz and felspar make up the colourless components of the rock. There is a considerable amount of quartz which does not show cataclasis or undulose extinction. Part of the felspar is saussuritised and part is quite clear. Labradorite has been recognised, but as some pieces of felspar have a lower refractive index than basal quartz, there is some andesine or oligoclase as well. Fragments of garnet are occasionally set in the felspar areas. Ilmenite, sphene, and apatite are accessory minerals.

The rock may be described as an augite amphibolite.

We are inclined to think that this rock is related to the dyke bands at the Cape Pigeon Rocks, in the same manner that the coarse-grained amphibolites (No. 9) at Cape Denison are related to the corresponding amphibolite dykes. This example differs from the coarse amphibolites of Cape Denison in the possession of augite and garnet; but in a like manner the altered dykes at the Cape Pigeon Rocks differ from the Cape Denison series in the possession of augite and garnet.

The history of the coarse-grained patches at Cape Denison is considered to be probably associated with great stress which has rendered former dyke channels discontinuous. It is interesting to note that the area near No. 786 at the Cape Pigeon Rocks has suffered intense crumpling (Plate XXV., fig. 2).

Garnet Point.

Among the specimens of altered dyke rock from this locality two varieties have been collected. The extraordinary features along the junction with the cyanite biotite gneiss of one type of amphibolite (No. 769 or 781) have already been mentioned. In this case a mineral which has been referred to as cyanite appears in the cyanite biotite gneiss, and can be traced across the junction to a distance of at least 1in. away from it. At this distance it is less abundant than in the cyanite biotite gneiss. It is found in all the specimens of amphibolites from this locality.

In this amphibolite hornblende is the most important constituent; but of nearly equal importance are the circular areas of diablastic felspar and pyroxene (Plate VII., fig. 4). These areas are similar in outline to some of the felspar-pyroxene areas in No. 942, or to the felspar-garnet areas in No. 953 from Stillwell Island. This rock, like No. 953, also possesses a noticeable amount of quartz; but nowhere do we find the pyroxene fragments set in quartz. Occasionally the fibres of pyroxene are set radially in the felspar. The pyroxene in the aggregates may be altered to hornblende or to a cloudy fibrous mineral. Very often, when it can be determined, the pyroxene has straight extinction. The aggregates may be dotted with ilmenites and small biotites, while in polarised light they nearly always show a little scapolite, arising out of a fibrous mass. Sometimes a mineral with high refractive index and low bluish polarisation colours can be detected and suggests a zoisite. The felspar in the aggregates may be clear and possess very fine, irregular, twin lamellæ. The low refractive index, high polarisation colours, and straight extinction of the scapolite can always be observed, but its determination is rendered more certain by the observation of uniaxial character and negative sign in the second amphibolite from this area.

Garnet is present, but in most slides protracted search is required to find the small pieces of garnet that may be set in the felspar. A portion of one slide, however, contains considerable garnet. This garnet is very ragged in outline and contains inclusions of felspar, biotite, ilmenite, and a colourless, brightly polarising mineral, probably scapolite. The decomposition of garnet into pyroxene cannot be observed in these rocks in the manner recorded in the Saxon area.

The relation of the pyroxene-felspar areas to the garnet is difficult to determine in this section. We know they are connected by our study of other sections, and in this instance the aggregate is occasionally replaced by garnet. Scapolite is observed to be included in the garnet and in the pyroxene areas, but it does not seem possible to say whether the pyroxene felspar has been developed from the garnet or *vice versa*.

The rock may be described as an amphibolite which is related both to the garnet amphibolites and to the hornblende plagioclase pyroxene gneisses.

No. 799.—The second type of amphibolite from Garnet Point is distinguished from the preceding by a complete absence of the diablastic areas of pyroxene and felspar and associated minerals.

The rock is a little more coarsely crystalline than most of the examples from Cape Gray and the Cape Pigeon Rocks and the granoblastic structure is again prominent. The mineral proportions may be indicated by the following:—

Hornblende	57·7
Felspar and quartz	35·3
Pyroxene	2·3
Garnet	1·2
Iron ore	1·2
Biotite	0·3
Apatite	0·3
Sphene	0·1
Residue, including scapolite and talc	1·6

The green hornblende is again the most abundant constituent and it is occasionally fringed with a little blue glaucophane. At other times an irregular brown tinge is noticeable in some crystals. The felspar is just as clear as the quartz from which it is difficult to distinguish in ordinary light, because their refractive indices are nearly the same. The felspar is an andesine, and the quartz may be set as rounded blebs in the hornblende as well as in the felspar, producing a poikiloblastic structure. There is, however, much more felspar than quartz.

The 2·3 per cent. of pyroxene is localised in one part of the slide, where it is nearly as abundant as the hornblende. The clear portion has a very pale green colour, but some of it is turbid and dense. Hypersthene is present because a large number of grains show straight extinction. Monoclinic pyroxene is also present because an extinction angle of 37° has been measured. The garnet is again invariably set in felspar (Plate VII., fig. 3). Some crystals are very small and fragmentary but yet perfectly clear and unaltered. Bigger individuals, granular in outline, appear in the larger areas of felspar.

There are areas in this slide which seem to be analogous to the shear planes that are recorded in Nos. 767 and 771 at the Cape Pigeon Rocks. The bulk of these areas are included in the 1·6 per cent. residue in the percentage mineral composition. In this case these areas have no linear trend except that the pyrite in part seems to occupy a definite plane; but the analogy is found in their mineral content. The areas are noted for an abundance of fuzzy material which has high polarisation colours and which may be finely granular talc. Equally prominent with this talc is a colourless hornblende which may be bordered with blue glaucophane. The colourless hornblende is often feebly pleochroic and sometimes contains patches of normal green hornblende. Sometimes the plates and fibres are bent or broken, and if an extinction angle of 30° can be measured it is interpreted as a colourless pyroxene. There are more prominent areas of scapolite associated with these shear areas along the edge of the slide.

Though the garnet percentage is small it is distinctive and the rock may be called a garnet amphibolite. This name indicates its relation to the garnet amphibolite of Stillwell Island (No. 953), though the garnet percentage of the latter is many times greater.

Chemical Characters of the Cape Gray Dyke Series.

The following chemical analyses of four members of this series of rocks have been made by Messrs. P. G. W. Bayly and J. C. Watson, in the Victorian Geological Survey Laboratory:—

	I.	II.	III.	IV.
SiO_2	47·74	49·91	49·99	48·06
Al_2O_3	15·10	13·02	13·84	14·19
Fe_2O_3	2·47	2·84	1·97	1·95
FeO	12·43	13·70	13·18	15·66
MgO	6·85	4·74	6·01	5·29
CaO	9·41	9·28	9·72	9·24
Na_2O	2·09	2·03	1·94	0·71
K_2O	0·61	0·83	0·79	1·29
H_2O +	0·73	0·87	1·40	1·21
H_2O −	0·19	0·12	0·05	0·13
CO_2	n.d.	tr.	tr.	n.d.
TiO_2	1·83	2·39	1·78	2·54
P_2O_5	0·30	0·20	tr.	0·28
SO_3	nil	nil	nil	n.d.
Cl	tr.	tr.	str. tr	n.d.
MnO	0·24	0·12	0·07	n.d.
NiO, CoO	0·02	0·01	0·01	n.d.
CoO	p.	p.	p.	n.d.
LiO_2	tr.	str. tr.	tr.	n.d.
Total	100·01	100·06	100·75	100·55
Sp. Gr.	3·0988	3·1283	3·0974	3·2457

	Group Values.							Projection Values.		
	S.	A.	C.	F.	M.	T.	K.	a.	c.	f.
I.	52·9	2·5	7·0	28·1	3·8	—	0·9	1·3	3·7	15·0
II.	56·1	2·7	5·5	27·5	5·2	—	1·0	1·5	3·1	15·4
III.	54·8	2·6	6·1	27·7	5·0	—	1·0	1·4	3·4	15·2
IV.	54·4	1·6	7·4	27·6	3·3	—	1·0	0·9	4·0	15·1

I. No .773—Plagioclase Pyroxene Gneiss. Cape Gray, Adelie Land

II. No. 767.—Hornblende Plagioclase Pyroxene Gneiss. Cape Pigeon Rocks, Adelie Land.

III. No. 799.—Garnet Amphibolite. Garnet Point, Adelie Land.

IV. No. 953.—Garnet Amphibolite. Stillwell Island, Adelie Land.

There is a very strong family likeness in the chemical composition of the dyke rocks from these four localities. Each analysis has the general characters of a basic igneous rock and closely resembles that of the Cape Denison amphibolite (No. 629). The minor differences can readily be explained as primary variations in the compositions of the dykes at the separate localities.

It may be recalled, however, that the mineral compositions of these four rocks show great variation, and range from 45·3 per cent. pyroxene in the Cape Gray rock to 2·3 per cent. pyroxene in the Garnet Point rock; from 57·7 per cent. hornblende in the Garnet Point rock to 3·4 per cent. hornblende in the Cape Gray rock; from 19·7 per cent. garnet in the Stillwell Island rock to 1·2 per cent. garnet in the Garnet Point rock, and from 6·7 per cent. ilmenite in the Stillwell Island rock to 1·2 per cent. in the Garnet Point rock. These varying mineral combinations are independent of the chemical composition and are interpreted as due to varying metamorphic conditions. The similarity of the four analyses provides an argument for the general constancy of chemical composition during metamorphism.

The specific gravities of these rocks are all higher than the specific gravity (3·030) of the Cape Denison amphibolite, No. 629, which is considered to be a product of more superficial conditions. These higher specific gravities agree with the general deep seated metamorphism of Cape Gray Promontory. The garnet amphibolite from Stillwell Island has a value distinctly greater than the others, and this high value can be ascribed to the same cause as the production of garnet.

The general family likeness is reflected in the table of Osann group values and projection values. These group values place each rock in the group of eclogites and amphibolites. When the projection values are plotted they produce a cluster of dots around the mean projection value of this group (fig. 14).

The production of secondary pyroxene requires a high temperature factor, and the production of garnet requires a high uniform pressure factor during the recrystallisation. Rocks which contain these two minerals can confidently be classed as kata zone products. The plagioclase pyroxene gneiss of Cape Gray is a kata zone rock, though only the incipient forms of garnet are found. Hornblendisation of the pyroxene is looked upon by Grubenmann as a meso zone characteristic, and, therefore, the hornblende plagioclase pyroxene gneiss from the Cape Pigeon rocks represents a transition stage between the kata zone type and the meso zone type. Other dyke rocks described from the Cape Pigeon rocks are distinctly meso zone types.

The garnet amphibolites from Garnet Point and Stillwell Island are members of the garnet amphibolite family which Grubenmann places in the Meso division. The development of both garnet and hornblende from the pyroxene and felspar has been described from the same rock, but it cannot be considered to be proved that the garnet-forming conditions are the same as the hornblende-forming conditions. An increase of pressure without alteration in temperature may produce garnet, while a decrease of temperature without alteration in pressure may produce hornblende. The hornblende-forming conditions may follow the garnet-forming conditions. We think this is indicated by rocks like No. 942, which is similar to the garnet amphibolite in structure, but the garnet is replaced by pyroxene felspar areas. If, then, we place the garnet amphibolites among the meso zone rocks, it must be borne in mind that the same meso conditions do not produce both garnet and hornblende. The garnet amphibolites are not kata zone rocks and their family characteristics are too definite to allow them to be considered as transition types between the kata types and the meso types.

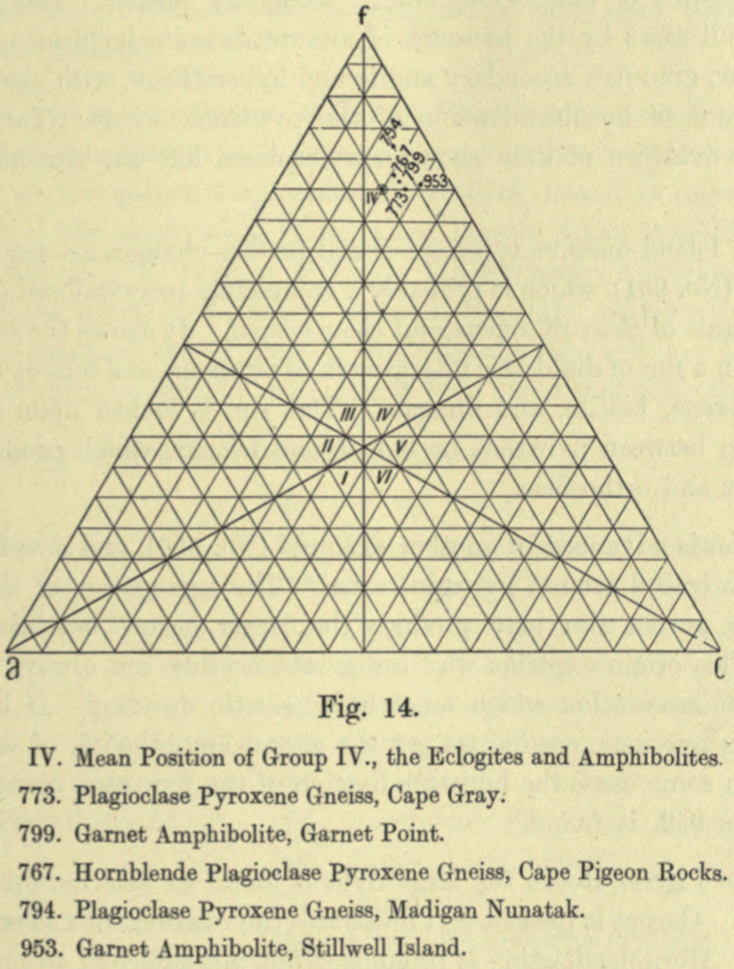

Fig. 14.

IV. Mean Position of Group IV., the Eclogites and Amphibolites.
773. Plagioclase Pyroxene Gneiss, Cape Gray.
799. Garnet Amphibolite, Garnet Point.
767. Hornblende Plagioclase Pyroxene Gneiss, Cape Pigeon Rocks.
794. Plagioclase Pyroxene Gneiss, Madigan Nunatak.
953. Garnet Amphibolite, Stillwell Island.

The Crystalloblastic Order.

The crystalloblastic order for the plagioclase pyroxene gneisses appears to be—Pyroxene, hornblende; biotite; ilmenite; felspar. If garnet appears, as in No. 935, garnet is placed above the hornblende.

In the garnet amphibolite the order is—Garnet, hornblende, biotite, ilmenite, felspar, quartz.

SUMMARY.

In all exposures on the Cape Gray Promontory basic gneisses are found associated with the garnet gneisses. With one exception, these basic gneisses are found in dyke form which is so definite that the field examination convinced the observers of the igneous origin. Microscopic and chemical examination have confirmed this observation and interesting mineralogical changes have been traced.

At Cape Gray the outlines of primary felspar laths and augite crystals can be determined and a blastophitic structure is found. The primary felspars are now represented by aggregates of interlocking, clear, secondary felspar. The primary augite, recognisable in all cases by the presence of minute ilmenite inclusions, becomes transformed into clear, granular, secondary augite and hypersthene, with associated ilmenite. A varying amount of hornblendisation of the pyroxene occurs. The basic rocks at Cape Gray bear evidence of kata zone metamorphism like the surrounding cordierite garnet gneiss.

At Stillwell Island massive types occur and further changes are traced. A coarsely crystalline rock (No. 951), which is probably a completely recrystallised dolerite, consists of granular crystals of clear pyroxene and clear felspar. It shows the incipient changes of modification in a rim of diablastic intergrowth of pyroxene and felspar which surrounds crystals of pyroxene, biotite, and ilmenite. This rim is looked upon as the incipient stage of reaction between pyroxene or biotite and felspar, which produces garnet and quartz or garnet and orthoclase.

This reaction is advanced in another example (No. 935), and a well developed rim of garnet can be traced around pyroxene areas. The aggregation of the small garnets which form the garnet rim may produce the larger garnet crystals of the garnet amphibolite. This origin explains why the garnet crystals are always set in a felspar base—a constant association which must have genetic meaning. If hornblendisation of the remaining pyroxene occurs, we get the garnet amphibolite, of which No. 953 is an example. In some cases the hornblendisation of the pyroxene occurs and a normal amphibolite, No. 952, is found.

At the Cape Pigeon Rocks the large dyke is found to be a hornblende plagioclase pyroxene gneiss. Garnet is present and illustrates the relation with some of the Stillwell Island gneisses. Hornblendisation is prominent but not sufficient to mask the relation of the gneiss to the plagioclase pyroxene gneisses. The narrower dykes on this area show a much greater degree of hornblendisation than the large dyke. The percentage of pyroxene decreases from 26·8 per cent. to 7·6 per cent. in No. 782, and is zero in others. These last are amphibolites. A coarser amphibolite comes from this area which did not maintain the dyke form in the field. It is a rock which is clearly related to the dyke rocks, and the relation is considered to be the same as that between the coarse-grained amphibolite patches at Cape Denison (No. 9 type) and the well-defined dyke bands.

The presence of definite shear planes has been noted in two examples from this locality. The shear plane may look like a thin vein in the hand specimen, and under the microscope is marked by decrystallisation. The hornblende and biotite may become very pale and even decolourised. The presence of finely granular talc is indicated, and pyrite is distributed linearly along the shear plane.

At Garnet Island two types of amphibolite have been described. One type is noted for the abundant circular areas of pyroxene diablastically set in felspar. The pyroxene is sometimes altered to hornblende and sometimes to a fibrous product. Scapolite is frequently discovered in these areas. Rarely these areas are replaced by ragged garnets; but no definite evidence can be gathered to show that the garnets break up into pyroxene and felspar.

The second type of amphibolite at Garnet Point carries a small garnet percentage evenly distributed through the rock. Again the garnet is always set in a felspar base, and a relation to the garnet amphibolite of Stillwell Island is indicated. Features, similar to those in the shear zones in the Cape Pigeon Rocks, are also found, but no definite linear direction is obvious in them. Decolourised hornblende and talc are prominent in these areas, and the colourless hornblende may be fringed with blue glaucophane. Sometimes the crystals of colourless hornblende are bent and broken and linear pyrite may be found. Scapolite is here associated with these areas.

The various types may be summarised thus—

	No.	
Cape Gray	773	Plagioclase Pyroxene Gneiss.
	766	Hornblende Plagioclase Pyroxene Gneiss.
Stillwell Island	951	Plagioclase Pyroxene Gneiss.
	942	Hornblende Plagioclase Pyroxene Gneiss.
	935	Garnet Plagioclase Pyroxene Gneiss.
	953	Garnet Amphibolite.
	952	Amphibolite.
Cape Pigeon Rocks	767	Hornblende Plagioclase Pyroxene Gneiss.
	782	Augite Amphibolite.
	771	Amphibolite.
	786	Augite Amphibolite (without dyke form).
Garnet Point..........	781	Amphibolite.
	799	Garnet Amphibolite.

Four chemical analyses of this rock series are given. These show a strong family likeness and possess the general characters of basic igneous rocks. The Osann group values place them quantitatively in the group of eclogites and amphibolites. The plagioclase pyroxene gneisses are placed in the kata division of this group and the amphibolites belong to the meso division. The hornblende plagioclase pyroxene gneisses are transition members between the two divisions.

The general similarity in field characters and in composition at the four localities permit the assumption that the altered dykes in each area are part of one intrusive series. Differences in all cases can be ascribed to varying metamorphic conditions.

There is no direct evidence to correlate this intrusive dyke series with the Cape Denison metamorphosed dyke series; but all differences can again be explained by varying metamorphic conditions. The dominating factor among the metamorphic conditions at Cape Denison is strong stress, whereas the general metamorphic conditions in the Cape Gray series involve high uniform pressure and high temperature with only subordinate stress. The strong stress at Cape Denison has destroyed all those finer features of dyke form which have been preserved at Cape Gray. The differing mineral suites are considered to be a direct reflection of the different conditions during recrystallisation.

CORRELATION.

The basic pyroxenic gneisses are found in many areas of the crystalline schists. In the classical area of the Saxon pyroxene granulites there are examples to which members of the Cape Gray series are analogous. The fine grained plagioclase pyroxene gneiss (No. 773) is similar to the pyroxene granulite from America near Penig.* This Saxon type, however, is described as schistose, whereas the Cape Gray rock is massive and relic dolerite structures are recognisable. There is an analogy between the garnet amphibolite from Stillwell Island (No. 953) and the pyroxene granulite from Bahnstation, Wittgensdorf; † but the hornblende in the former is replaced by pyroxene in the latter. The manner in which the garnets are set in a colourless base in the Antarctic rocks is a phenomenon that also appears in the Saxon rocks illustrated on Table XXIII., figs. 3, 5, and 6, of Lehmann's memoir. There is also a likeness between the pyroxene granulite from Chemnitzbiege, by Mohsdorf,‡ and the amphibolite No. 769 from Garnet Point. In No. 769 there is little garnet, but the structures are similar in both. In this Saxon example Lehmann considers that the separation of the pyroxene occurs at the expense of the garnet, whereas Holland has found the reverse to be true in some of the Indian rocks.§ Other observers have formed similar conclusions to both Lehmann and Holland. In our observations we have been led to suspect evidence for Lehmann's position and we obtained definite proof in favor of Holland's position. The explanation probably lies in the fact that the reaction which involves both pyroxene and garnet is a reversible one. The direction in which the reaction goes is determined by the external conditions.

The same class of rock has been described among the pyroxenic and hornblendic gneisses by Lacroix, in India and other places.|| The pegmatoidal pyroxene, set in oligoclase and quartz, that is figured by Lacroix (p. 179) is similar to some of the structures described as diablastic, *e.g.*, No. 942.

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* "Entstehung der Altkrystallinischen Schiefergesteine," J. Lehmann, Bonn, 1884, Tafel XXIII., fig. 2.

† Tafel XXIII., fig. 3.

‡ Tafel XXIV., fig. 5.

§ "Origin and Growth of Garnets," T. H. Holland, Rec. G.S.I., vol. XXIX., p. 20.

|| "Gneissose Rocks of Salem and Ceylon," Lacroix, trans. by Mallet, Rec. G.S.I., XXIV., p. 155.

Similar rocks have been described by Holland as norites among the charnockite series of India.* The augite norite and the hornblende augite norite present analogies to the plagioclase pyroxene gneisses. Yet they are, perhaps, more comparable with the basic gneisses at Madigan Nunatak and Aurora Peak; but the latter rocks have a direct relation to the Cape Gray dykes.

In his description of plagioclase pyroxene rocks from Parasnath and the Ijri Valley, from the Madras Presidency and Bengal, Holland † describes the original augite as darkened, almost blackened, by minute rods and plates forming an ordinary example of schillerisation. The hornblende which is derived from the augite is free of such inclusions. This augite reads precisely similar to the primary dusty augite that has been described from Cape Gray and Stillwell Island. The development of secondary pyroxene has not occurred in the Indian rock as in the Antarctic.

In some of the pyroxene granulites or basic charnockites from the neighbourhood of Salem, Holland ‡ describes a corona of garnet around the hypersthene. This seems to be similar to the corona around the pyroxene in the garnet plagioclase pyroxene gneiss (No. 935) from Stillwell Island. In this publication a sketch is given of hypersthene with a corona of spongy garnet. This spongy garnet appears to be similar to what we have referred to as diablastic pyroxene, or vermicular pyroxene, which is very well developed in some of the Stillwell Island rocks. This material is sometimes isotropic, sometimes with very low polarisation colours, but sometimes it shows the brighter polarisation colours of pyroxene. Possibly it is not constant in composition and represents some intermediate form between garnet and pyroxene. The separation of quartz in this garnet-pyroxene reaction is noticed in the Indian rocks as well as in the Stillwell Island rocks.

Similar pyroxene gneisses have been described in many parts of the world, in Canada, in Scotland, in Madagascar, from the moraines in South Victoria Land, and in many other places.

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* "Charnockite Series," T. H. Holland, Mem. G.S.I., XXVIII., pt. 2, p. 156.

† "Origin and Growth of Garnets," T. H. Holland, Rec. G.S.I., vol. XXIX., p. 20.

‡ "Geology of the Neighborhood of Salem," T. H. Holland, Mem. G.S.I. 30, p. 12.

CHAPTER XII.

1.—RELATION BETWEEN THE ROCKS AT CAPE GRAY, MADIGAN NUNATAK, AND AURORA PEAK.

We have shown in our descriptions that the two rock types found at the Madigan Nunatak correspond closely with the two chief types at Aurora Peak. If we subtract the epi zone metamorphism from the Madigan Nunatak rocks, and the meso zone metamorphism from the Aurora Peak rocks we get, in both cases, kata zone metamorphic types. The basic rocks of the two localities then become identical and the acid rocks are analogous; but they all agree in possessing a granulitic structure and the mineral hypersthene.

The basic rock at Aurora Peak is reported as a dyke cutting across the foliation, but, though the basic rock at Madigan Nunatak appeared to form a band, nothing definite could be observed in the field. Still, from general considerations, it has been considered to be probably a metamorphosed basic igneous rock. The likeness to the Aurora Peak rock renders this more probable, but it receives striking confirmation by comparison with the undoubted dyke at Cape Gray.

We place here, side by side, the mineral proportions, determined by the Rosiwal method, of No. 773 (the plagioclase pyroxene gneiss from Cape Gray), of No. 794 (the plagioclase pyroxene gneiss from the Madigan Nunatak), and of No. 759 (the hornblende plagioclase pyroxene gneiss from Aurora Peak). We add, for the sake of comparison, the mineral proportions of a hornblende norite from St. Thomas Mount, Madras, determined by Washington.*

	No. 773.	No. 794.	No. 759.	Hornblende Norite, Madras.
Felspar	40·5	42·5	44·8	40·8
Pyroxene	45·3	45·5	28·6	31·0
Hornblende	3·4	3·3	15·5	19·6
Iron Ores	6·6	8·4	10·1	8·6
Biotite	4·2	0·3	0·3	—
Apatite	—	—	0·7	—
Approx. average absolute grain size ...	0·05mm.	0·30mm.	0·17mm.	—

The likeness of the proportions of felspar and ferromagnesian minerals in all four cases is obvious. The pyroxene of No. 773 is partly secondary and partly primary; but the secondary pyroxene is very similar in type to the pyroxene of Nos. 794 and 795.

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* "The Charnockite Series of Igneous Rocks," H. S. Washington, Amer. Journ. Sci., Vol. XLI., 4th Ser., 1916, p. 323.

Orthorhombic and monoclinic forms are present in each case. The primary augite in No. 773 contains abundant minute inclusions of ilmenite, and these were neglected in the count of iron ore. There is, therefore, reason for the smallest iron ore percentage in No. 773.

Thus the proportions of felspar and pyroxene in the plagioclase pyroxene gneiss at Cape Gray with average absolute grain size approximately 0·05mm., whose primary dyke origin is beyond all possible doubt, are practically identical with the proportions in the epi plagioclase pyroxene gneiss (pyroxene granulite) at Madigan Nunatak with average absolute grain size approximately 0·30mm. The minerals are in each case the same, and there is no important difference in the chemical composition, and they are not far removed from one another in the Ozann triangular projection. The chief difference between these two rocks is the grain size. The fine grained type, No. 773, possesses the relic structure and is most like the primary dolerite. Hence we can conclude that the metamorphic conditions at Madigan Nunatak were longer continued and caused certain crystals to enlarge themselves at the expense of other crystals, thus producing fewer and larger crystals. The fine-grained facies has been replaced by a coarse-grained facies.

We have the direct evidence that the felspar and pyroxene of a coarse-grained dolerite at Cape Gray have been replaced by a fine granoblastic aggregate. Secondary enlargement of these fine grains can proceed till we get an aggregate many times coarser. If the pyroxene in the aggregate be then partially converted into hornblende we get the meso plagioclase pyroxene gneiss at Aurora Peak which is identical with the rock called hornblende norite from St. Thomas Mount, Madras. If the hornblendisation of the pyroxene be completed, an amphibolite, comparable to those at Cape Denison would result. If the conditions of hornblendisation are replaced by those of the epi zone of metamorphism a certain amount of granulation appears, and we find some crystals are fractured, some are crushed, and some have granulated selvages as in the Madigan Nunatak example. The direct transition stages between dolerite and amphibolite have not been directly traceable in these areas as it has been done in other parts of the world.

The two-phase metamorphism of these basic rocks at the nunataks is considered to rest on direct and sure evidence. Therefore it is not reasonable to doubt the interpretation of a two-phase metamorphism of the acid hypersthene gneisses which are associated with and intruded by the basic rocks. Subtracting respectively the effects of epi and meso zone metamorphism, we find a family likeness which is exhibited by the granoblastic structure and the presence of hypersthene. We attribute this family likeness to kata zone metamorphism.

As we have shown that the hypersthene is a metamorphic product in the plagioclase pyroxene gneiss, it is little assumption to assert that the hypersthene is also a metamorphic mineral in the acid hypersthene felspar gneisses which have suffered similar conditions of recrystallisation. Indeed, the definite parallel arrangement of the hypersthene crystals would be difficult to explain on any other hypothesis. In many metamorphosed granites and similar rocks the ferromagnesian percentage is expressed in a content of biotite or chlorite. If the temperature of the metamorphism should exceed that at which biotite is capable of holding its water of combination, what will be the product? Pyroxenes are high temperature minerals and it would not be unreasonable, on *a priori* grounds, to expect biotite to be replaced by pyroxene under such circumstances. If there were sufficient lime in the rock we might equally well expect garnet, provided the pressure factor is suitable. Biotite has been proved to be an alteration product of hypersthene in the zone of the gneissic dacites at Belgrave, Victoria.* Hence the metamorphism of a granite under conditions of high temperature, high uniform pressure, and weak stress, might produce a hypersthene alkali felspar gneiss. Apart from such considerations, however, or any correlative evidence, the study of the rock relations has made it clear that hypersthene is a metamorphic mineral in the basic rocks and, as these and the acid hypersthenic gneisses have suffered complete recrystallisation under similar conditions, it is unreasonable to deny the metamorphic character of the hypersthene in the acid gneisses.

To this complete recrystallisation under similar conditions we must assign the family likeness of the Madigan Nunatak and the Aurora Peak rocks, in spite of chemical differences. On the other hand we must ascribe the differences between the gneisses at Aurora Peak and at Cape Denison to dissimilar conditions of recrystallisation, in spite of marked chemical likeness. The Cape Denison granodiorite gneiss is almost a product of epi zone conditions.

We think that it is impossible to deny the metamorphic character of these acid hypersthenic rocks, and yet we find that they correspond very closely with the description of the hypersthenic rocks of Peninsular India, which have been called the Charnockite Series. We have already demonstrated the similarity in chemical composition of the acid and basic types at the Madigan Nunatak to members of the Charnockite Series; and we have just found that the mineral composition of the hornblende plagioclase pyroxene gneiss at Aurora Peak is very close to that of a hornblende norite, a basic charnockite from the type locality, St. Thomas Mount, Madras. But the charnockites have been considered by Holland † to be igneous rocks which have consolidated under phenomenal conditions. Can, then, these Antarctic metamorphic rocks be strictly compared with igneous rocks, or is it possible that the charnockites are really metamorphic rocks? It behoves us to critically examine the evidence.

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* "Gneisses and Dacites of the Dandenong District," E. W. Skeats, Q.J.G.S., vol. LXVI., 1910, pp. 450-469.

† "The Charnockite Series," T. S. Holland, Mem. G.S. India, XXVIII., pt. 2. Numbers in brackets in the following refer to pages in this publication.

2.—THE CHARNOCKITE SERIES.

The charnockites are a group of crystalline rocks which appear among the Archæan gneisses in Southern India. The distinguishing features of the unaltered members of the series (p. 125) are the constant even-grained granulitic structure and the constant presence of the mineral hypersthene, while garnet uniformly appears in the gneissose forms, just as in the Antarctic rocks. The chief types range from acid charnockite and leptynite (granulite) to basic norites and ultrabasic pyroxenites and hornblendites. They are a series which possesses resemblances to the Saxon pyroxene granulites and the French pyroxene gneisses, and to other ancient pyroxenic eruptives; but they are determined from evidence within the series itself to be of igneous origin. At times they are acknowledged to have suffered some alteration, but the igneous character is held to be dominant.

The pyroxene granulites and the pyroxene gneisses are looked upon as crystalline schists, and hence it must be considered possible, apart from Antarctic evidence, that the charnockites are similarly so. Besides, we are told (p. 195) that the charnockites are quite old enough to be affected in the same way as the Dharwar system of crystalline schists.

The charnockite series groups together acid and basic rocks in a way that is known to be (p.154) contrary to the usual practice of petrographical (igneous rock) classification, and Holland (pp. 131, 210) is quite aware that metamorphism tends to reduce points of difference between rocks of diverse origin and to produce similarity. Holland is also aware that the granulitic structure (p. 154) with general absence of idiomorphism favours a metamorphic origin, but he believes that a granulitic structure may result from disturbance of the magma during the process of consolidation. This belief rests on the observation that dykes of pyroxenite cut the norites, and the igneous origin of the pyroxenite cannot, therefore, be doubted. But this observation does not preclude the possibility that the pyroxenite dyke and the norite have suffered similar metamorphic conditions during which the dyke characters have been preserved in the same manner as at Cape Gray. Such grouping, then, of the charnockite series indicates the outstanding nature of the genetic relationship between the various members.

Now we find (p. 125) that nearly all varieties possess a linear arrangement of the constituent minerals, *i.e.*, a foliation. In the case of rocks of St. Thomas Mount and Pallavaram the direction is constant between N.N.E. and S.S.W. Holland insists that this foliation is not a metamorphic feature, because it may occur (p. 125) in rocks with a complete absence of all signs of crushing, and because (p. 137) the most delicate interlocking structures may be preserved, and all signs of dynamo metamorphism are wanting. Hence Holland concludes that this disposition of the minerals occurred before consolidation. It seems to us that the degree of dynamo metamorphism is here determined wholly by the amount of induced mechanical structures, *e.g.*, granulitisation, mylonisation, etc., and that this is an instance that would justify Wienschenk's criticism of the term dynamo metamorphism and his introduction of the terms piezo contact metamorphism, etc. It must now be considered a fundamental fact that mechanical structures are often absent in thoroughly recrystallised rocks. We have elsewhere argued that the gneissic foliation in granites and similar rocks is always a metamorphic feature in that it involves a rearrangement of crystals after, not before, consolidation. We reached this conclusion because stress is considered to be an essential factor in its production. Holland acknowledges the action of stress in saying (p. 125) that " the crystals are arranged with their long axes at right angles to the direction of maximum pressure." But when he adds " before consolidation " he is implying the action of a stress through a liquid which is impossible. Holland's interpretation of the foliation and banding has produced the chief difficulty in the determination of the charnockites as metamorphic rocks.

If this difficulty be removed there is no barrier to the interpretation of the charnockites, like the Antarctic rocks, as a suite of igneous rocks that have suffered complete recrystallisation under the conditions of the kata zone of metamorphism. The demonstration of the primary igneous character by the form and structure of the great massif, by the existence of dykes and apophyses proceeding from the main mass and by the presence of included fragments of foreign rocks, is unaffected by the acknowledgement of kata zone metamorphism. Nor is the chemical and mineralogical evidence affected. Recrystallisation under kata zone conditions (high uniform pressure, dominating largely over stress and high temperature) does not destroy the dominating igneous structures, *e.g.*, the dyke structures at Cape Gray are so wonderfully clear that, foliation being almost absent, no metamorphism was suspected in the field. Observation of destroyed dyke structures are found restricted to areas where strong stress is evident. It seems to us that a metamorphic history applied in general to the Charnockite series, together with a double metamorphic history in those cases where mechanical structures are evident, satisfies the recorded evidence including the supposed igneous abnormalities.

The inclusion of rounded blebs of quartz in the felspar (quartz de corrosion) is a metamorphic structure analogous to the case of rounded blebs of quartz or felspar in the hornblende. The dissociation of felspar into microperthitic intergrowths is frequently associated with metamorphism, and it is also to be noted that the hypersthene is associated with a similar greenish alteration product in both the Indian and Antarctic rocks.

We are also inclined to read further evidence of recrystallisation after the primary consolidation of the associated rocks in the frequent observation of crystalline continuity across junctions. Sections cut across the junction of quartz felspar veins (p. 145) which cut across the charnockite and which bear the same family likeness, show no abrupt junction but a line of interlocking crystals. The same crystalline continuity is present across the junction of quartz veins in the norite (p. 157), across the junction of pyroxenite and norite, and across the junction of tongues of charnockite (p. 226) which ramify the biotite gneiss, while there is a gradual passage from charnockite to garnetiferous leptynite (granulite). Such crystalline continuity is, therefore, quite independent of the nature of the rocks, and is most likely an impressed metamorphic character. In specimens showing a junction from the Cape Gray Promontory there is a gradual microscopic transition from one rock to the other.

In describing the garnetiferous leptynite as a pressure altered form of charnockite (p. 142), Holland assumes that the set of metamorphic conditions which produced the granulated selvages has also produced the garnet. He argues that the temperature of crushing must be high. It can be pointed out that such is unnecessary as the acquisition of mechanical structures may be subsequent to the development of the garnet.

The typical augite norite from St. Thomas Mount (p. 156) is very similar to the plagioclase pyroxene gneiss at the Madigan Nunatak minus the mechanical structures, but the hornblende plagioclase pyroxene gneiss from Aurora Peak seems identical with the more common form of hornblende augite norite. If this comparison is correct we would expect that the hornblende is derived at the expense of the pyroxene, but I have not noticed this to be stated in references to the norites. Amphibolisation of pyroxene in the pyroxenites, an ultrablastic form of the charnockites, is described (p. 169), and it is noted (p. 170) that, whenever hornblende becomes a prominent constituent of the pyroxenites, the norites have also a conspicuous amount of hornblende. This amphibolisation is, therefore, a character which has probably developed by the impress of certain external conditions which have affected both the norite and pyroxenite together, *i.e.*, it is a recrystallisation subsequent to the formation of both pyroxenite and norite, and hence a metamorphic character. If the whole series of charnockites be metamorphic this development of hornblende may belong to a second metamorphic phase. Similar evidence of metamorphism is reported from the Nilgiris. It is stated (p. 121) that where the charnockite series is garnetiferous, the coarse-grained segregation or contemporaneous veins composed of quartz, felspar, and hypersthene also include garnet. Like the hornblende the distribution of the garnet is not controlled by igneous boundaries.

It is to be noted that, in using the term norite for these rocks, Holland is quite aware (p. 153) that they possess different appearance from olivine norite and augite norite which can appear as normal dyke rocks. If the metamorphic character be upheld this fact should not permit the retention of the name "norite." The norites, rich in garnet, should be acknowledged as metamorphic rocks, because Holland considers that the garnet, with its numerous characteristic inclusions, is formed from the pyroxene.

Where we find a description (p. 186) of pegmatoidal pyroxene plagioclase rocks in the Nilgiri mass we may read further metamorphic evidence. These rocks occur in lenticular masses which appear in trains along the same band of charnockite. The lenticular shape is looked upon as the result of the pinching of a once continuous band of charnockite, and in view of the Cape Denison phenomena this is quite consistent with metamorphic action. The pegmatoidal structure described between the felspar and pyroxene in these rocks reads like a known metamorphic structure, and the amphibolisation of the pyroxene certainly is.

Finally, it may be pointed out that the so-called abnormal igneous features (p. 244) find ready explanation on this metamorphic hypothesis. Whereas the granulitic structure and the almost complete absence of pronounced porphyritic crystals are remarkable for large masses of igneous rock, they are normal features in large masses which have been thoroughly recrystallised under kata zone conditions. The frequent presence of garnet cannot be adequately explained by an igneous hypothesis supplemented by subsequent mechanical deformation, and the parallel arrangement of the constituent minerals requires the action of stress after consolidation. If the pressure during recrystallisation were wholly the hydrostatic type no foliation would result, but such cannot be generally expected. The small amount of foliation denotes a weak stress.

An acknowledged metamorphic character can readily admit a variety like biotite pyroxene gneiss referred to by Fermor,* and considered by Holland to be probably an abnormal member of the charnockite series.

3.—THE "INFRAPLUTONIC ZONE" HYPOTHESIS.

Could the conclusion concerning the metamorphic nature of the charnockite series be avoided if we accept Fermor's conception of an infraplutonic zone ? In this hypothesis Fermor postulates the existence of a shell in the earth's crust, situated below the depth at which plutonic rocks consolidate, and characterised by garnets. The shell must lie at considerable depths, and the temperature and pressure are very high. It extends round the earth, and the whole of it is a potential magma.†

Fermor's theory arises from the study of an area of garnetiferous and manganiferous rocks which have been named the "Kodurite Series." In certain members of this series Fermor discovered that a calculation of the specific gravities of the mode and norm of the spandite rock (Ca-Mn garnet), and of kodurite (orthoclase, Mn garnet and apatite), showed that the spandite rock occupied 20 per cent., and the kodurite 10 per cent., smaller volume than its norm. Such indicates that the conditions favourable to the formation of garnet rocks are those of high pressure. If high pressure conditions have prevailed in the case of the kodurites, Fermor expects to find garnets in the various rock series associated with the kodurites. As this is so, he then suggests that eclogite must be a high pressure form of gabbro. It may be pointed out that eclogite has already been considered as a high-temperature and high-pressure alteration form of gabbro,* and further, that it is a product of the kata zone of metamorphism in which Grubenmann has recorded garnet as a common mineral.†

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* "Manganese Deposits of India," L. L. Fermor, pt. II., p. 245, Mem. G.S.I., 37.

† "Preliminary Note on Garnet as a Geological Barometer and on an Infraplutonic Zone in the Earth's Crust," L. L. Fermor, Rec. G.S.I. XLIII, pt. I., 1913.

The hypothesis has only been put forward, so far, in a short preliminary paper in a general manner. The absence of detail and of references makes it difficult to arrive at a just estimate of its worth. The shell is supposed to be normally solid, and only becomes liquid on release of pressure ; yet the constituents in this zone are, in a general way, spoken of as "crystallising out." The phrase, "crystallising out," is generally used in reference to magmas and solutions, but it may be applied to solid solutions. Fermor does not indicate that he is referring to solid solutions.

In the infraplutonic zone the formation of garnet occurs in those reactions and rearrangements which are accompanied by reduction of volume and absorption of heat ; and he points out that the formation of garnet from other minerals, such as pyroxenes, olivines, and iron ores, is always accompanied by decrease in volume. But he does not offer any explanation as to how the pyroxene, olivine, and iron ore happen to reach the infraplutonic zone. If we are to suppose that some pre-existing rock is buried by earth movements to such a depth that it reaches the infraplutonic zone, we are merely imposing a set of metamorphic conditions upon the rock. In this case the infraplutonic zone is indistinguishable from a metamorphic zone defined by the particular set of conditions. If melting should follow the exit of the rock from the infraplutonic zone the rock will assume the characters of a normal eruptive rock. If melting does not occur with release of pressure, and it has not occurred in the garnet rocks that I have studied, a normal metamorphic rock would appear to result.

The difference between the infraplutonic zone and the kata zone of metamorphism has not been considered by Fermor. If there is a similarity we point out that the infraplutonic conception involves the worst feature of the conception of metamorphic zones, viz., that of depth. A metamorphic zone can only be adequately defined by a set of physico-chemical conditions, and not by varying depths in the earth's crust.

When a plutonic rock forms from its magma we date its existence as a unit from the time of its consolidation. The petrologist must, at present, be content to leave open the questions concerning the origin of the magmas, because "cosmogony can afford no firm foundation for *a priori* reasoning."‡ Perhaps we should do the same with the products of the infraplutonic zone. Perhaps an infraplutonic zone product is meant to be analogous to a plutonic zone product, differing only in the conditions of temperature and pressure under which it forms. If this is so the infraplutonic conception does not offer any explanation at all of the large number of garnet rocks which have formed by recrystallisation in the solid state, and whose former igneous or sedimentary origin can be traced.

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* "Ein Beitrag zur Keentnis der Eclogite und Amphibolite mit besonderer berucksichtigung der Vorkommnisse des Mittleren Otztales," Laura Hezner, published by Alfred Holder, Wien, 1903.

† Grubenmann, op. cit., vol. II., p. 83.

‡ "Natural History of Igneous Rocks," A. Harker, p. 4.

Contrary to Fermor's supposition we find on the close examination of a given garnetiferous area that some rocks may contain garnet while others do not. In all localities on the Cape Gray Promontory most rocks have been described with garnet, but in each case there are types without garnet. In some cases we have described the incipient stages of garnet formation. Further, we have found that the garnet-forming conditions are highly localised in the garnet hypersthene felspar gneisses of Stillwell Island and the Cape Pigeon Rocks. They may be present at one end of a specimen 3in. long, while totally absent at the other end. In these the evidence is quite definite that the garnet has formed by reactions between existing minerals without fusion, and the metamorphic nature is undoubted. Such pronounced variation is scarcely compatible with the infraplutonic zone hypothesis.

The infraplutonic hypothesis has been advanced also without consideration of those instances in which garnets are known to be products of magmas. It is well known that some garnets, like melanite, appear in alkaline volcanic rocks, and we also found garnet at Cape Denison appearing both in a large crystal, 6in. in diameter, and in graphic intergrowth with quartz in the same pegmatite associated with the granodiorite gneiss in which garnets are absent. We do not doubt at present, therefore, that some garnets may form directly from solution.

Until Fermor discusses this mode of formation of garnet and distinguishes the infraplutonic zone from the kata zone of metamorphism and points out its relative advantages, a geologist will be unable to use his conception. For the present we must conclude that it does not give a reasonable account of the origin of the charnockite series.

4.—THE KODURITE SERIES.

We have turned to the short accounts available of the kodurite series to discover whether this remarkable series, which is responsible for the infraplutonic hypothesis, is considered to possess any metamorphic traits. At the commencement we notice that Fermor* assumes that certain gneissose granites gain their foliated character because they were intruded at the time of the folding of the Dharwar series, while other granites, which were intruded subsequent to this series, have only a banded structure due to flow. We, therefore, anticipate an incomplete appreciation of metamorphic individuality, while it has already been pointed out by Cross† that further proof is required before geologists can be expected to accept the view of igneous origin.

In this publication we find that the kodurite series is stated (p. 244) to be part of an ancient group of rocks which include the charnockite series, a gneissose granite, calc gneisses, and the khondalite series (metamorphosed sediments). As we consider these rocks possess metamorphic characters, and as they all outcrop in the form of parallel bands, it is probable that the kodurite series, which also possesses the banded arrangement, likewise possesses such characters.

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* "Manganese Ore Deposits of India," L. L. Fermor, Mem. G.S.I., XXXVII., pt. 2, 237.

† "Problems of Petrographic Classification suggested by the Kodurite Series of India," W. Cross, Journ. Geol., XXII., 1914, p. 794.

Fermor admits the likeness to metamorphosed manganiferous sediments in some cases, but he is influenced by the belief that there is little or no evidence that the kodurite series has suffered much by earth movements. There remains, however, a suspicion that the " suffering from earth movements " means nothing more than the presence of mechanical crush structures.

Even if we admit, as in the case of the charnockites, the evidence of igneous origin, there remains the possibility of a metamorphic character superimposed upon the igneous character; and, if this were so, the rocks must be classed as metamorphic, because it is quite impracticable, as argued by Crook,* to classify altered rocks according to their original condition. We notice (p. 250) that the kodurite family likeness extends over types varying from acid to ultra-basic, *i.e.*, there is a family characteristic, as in the charnockites, which is independent of chemical composition, and which we interpret as a metamorphic character. One of the supports of the igneous hypothesis is the assumed magmatic differentiation, which depends on the observation that the more basic rocks (p. 254), such as spandite rock, occur as large patches or streaks, surrounded by zones of less basic composition, such as kodurite, in a general matrix of quartz felspar or felspar rock. In a general report for 1914 it is stated † that Fermor is inclined to replace this interpretation with the supposition of assimilation on a large scale, and to consider that a granite magma has bodily dissolved entire manganese ore deposits. Either of these hypotheses will be difficult to substantiate, but the discussion will not be complete without a consideration of metamorphic differentiation or metamorphic diffusion.

The full and detailed account of the petrology of these rocks is not yet published, but the information available suggests that there has not been full consideration of possible metamorphic characters.‡

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* " The Genetic Classification of Rocks," T. Crook, Min. Mag., XVII., 1914, p. 70.

† " General Report of the Geological Survey of India for the Year 1915," C. S. Middlemiss, Rec. G.S.I., vol. XLV., pt. 2, p. 103.

‡ In addition to the two references quoted there is " The Systematic Position of the Kodurite Series, especially with reference to the Quantitative Classification," L. L. Fermor, Rec. G.S.I., XLII., pt. 3, p. 208.

CHAPTER XIII.

THE GENERAL PROBLEM OF TRANSFERENCE OF MATERIAL DURING METAMORPHISM.

There is no fundamental difference between the processes which have been termed metamorphic diffusion and metamorphic differentiation. The two terms have been introduced for convenience. Metamorphic diffusion merely involves a migration of material in the solid rock during the recrystallisation, and has been studied along pre-existing junctions. Metamorphic differentiation requires, in addition to a migration, a segregation of migrated molecules. Metamorphic diffusion of some constituents is necessary to bring about metamorphic differentiation, and in this way a metamorphic differentiation product is also a metamorphic diffusion product; but the converse is not true. Both processes are probably governed by the same fundamental principles, and both involve the wide problem of the general transfer of material during metamorphism. The principle asserted in this problem is one that has not been accorded general acceptance chiefly on account of the paucity of sure evidence and the possibility of alternative hypotheses.

EVIDENCE OF MIGRATION IN GEOLOGICAL LITERATURE.

Chemical changes in total composition during metamorphism has been recently argued by Leith and Mead,* and each chemical change requires a migration. These authors look upon amphibolite as an end product of the metamorphism of marble. Though we see reason to question this view, we think that the phenomena described by Adams and Barlow † at the junction of a crystalline limestone and an amphibolite provide sound evidence of a transfer of material during metamorphism. Further examples are quoted by Leith and Mead. W. S. Bayley has provided the record in the Menominee District of Michigan that "at some places the dolomites at their contact with their overlying iron formation have been entirely changed from their original condition and are now represented by talc and serpentine." ‡ Such a change would involve an important change of composition. The transformation of quartzite into sericite schist is a change that has been substantiated by Truemann, but, so long as the authors ascribe the removal to the agency of solutions, it cannot be considered as evidence of the molecular transfer of material in the solid state during dynamo metamorphism. Strong evidence has been put forward by G. H. Williams, § who has traced a gabbro into a green-stone schist (sericite chlorite schist), and the alteration in composition is proved by chemical analyses. He correlates the chemical changes between fresh gabbro, saussuritised gabbro, and greenstone schist with varying amounts of chloritisation, sericitisation, and carbonation.

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* "Metamorphic Studies," C. K. Leith and W. J. Mead, Journ. Geol., vol. XXIII., 1915, p. 602.

† Op. cit., Adams and Barlow, p. 87.

‡ "Menominee Iron Bearing District of Michigan," W. S. Bayley. Mon. 46, U.S. Geol. Survey, 1904, p. 221.

§ "The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan." Bull. 62, U.S. Geol. Surv., 1890, p. 76.

Further evidence still is claimed in the theory advanced by Leith and Mead that there is a convergence under metamorphic conditions towards definite mineralogical types, chiefly hornblende, chlorite, or mica. If such a conception is warranted it does provide extra evidence. The unpublished text book referred to in their paper is now available,* but no detailed petrological study is forthcoming of the instances in which these types are produced. The theory depends largely on the comparison of groups of analyses of sericite schists, chlorite schists, and hornblende schists, which have been divorced from all field associations and from questions of origin. The theory at present remains a mere speculation until some knowledge is gained of the fate of that part of the chemical composition of the rock which must be rejected in order to produce hornblende, mica, or chlorite rocks. The theory further neglects to take account of those types of metamorphic products which are produced under metamorphic conditions incompatible with the existence of chlorite, hornblende, or mica, *e.g.*, pyroxene gneisses or any rock that is formed under the conditions of Grubenmann's kata zone where the normal structure is massive not schistose.

It may be suggested that the "convergence" theory is an incomplete expression of the theory of metamorphic differentiation, because it has been shown that hornblende rock, chlorite rock, and biotite-hornblende rock are formed by metamorphic differentiation. If it be subsequently found that metamorphic differentiation can only occur under those metamorphic conditions which tend to produce hornblende, chlorite, or mica, then there will be a closer agreement between the theories than is anticipated. As, however, we have instanced a large garnet crystal as a minute differentiation we must at least suppose that differentiation can occur under garnet-forming conditions which are normally those of the kata zone.

Some evidence, therefore, has been culled from the geological literature by Leith and Mead to establish the theory that some transference of material occurs during metamorphism. On the other hand a wealth of evidence can be obtained to prove that in many instances no important change has occurred. This, indeed, is the basic principle upon which Grubenmann has built his classification of schists. Hence the degree and range of the transference must necessarily be limited. No more than this is implied in the theory of metamorphic diffusion.

If transference of material occurs across a pre-existing junction of two rock types the junction will be replaced by a transition which we call a metamorphic diffusion product. Many examples of destroyed junctions have been described between igneous and sedimentary rocks, but in most cases it has been ascribed to assimilation of the sedimentary rock by the igneous. The examples have been looked upon as igneous phenomena, not metamorphic. Cole, for instance, describes a granite which, he claims, has invaded and partially absorbed amphibolite. " The various stages of absorption can be traced with the unaided eye. Lumps of amphibolite seem to swim in the gneiss and fade off into it, as if melting before our eyes. The gneiss becomes enriched with streaks of basic matter in which biotite begins to predominate over amphibole."* The same attitude has been maintained by Cole in his recent address to the British Association for the Advancement of Science,† and a list of references is quoted where similar passages between metamorphosed igneous and sedimentary rocks have been recorded in other areas. As far as it can be verified, all the instances could be given a metamorphic interpretation, in which case they become examples of metamorphic diffusion and provide evidence of the transfer of material during metamorphism. We cannot accept Cole's statement that amphibolite is the " final term of various metamorphic series." It is a statement in which considerable migration during metamorphism is tacitly assumed, and it is an unwarranted assumption when we reflect that Cole is endeavouring to apply the theory of contact metamorphism on the evidence of transition.

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* "Metamorphic Geology," C. K. Leith and W. J. Mead. New York, 1915.

A further example may be quoted from the Broken Hill region. Mawson states ‡ that where the metamorphic conditions are intense a passage of materials may take place from the intrusive rock into the intruded rock. He instances a gradation between quartzite and quartz felspar rocks east of Mookaie Hill. Mawson, however, is inclined to regard these transitions as part of a pneumatolytic effect.

An igneous magma may, of course, completely alter the character of the invaded sediments, but there still remain to be found the examples where a junction has been destroyed and replaced by transition types except where powerful stresses are evident. Even with the play of stresses such junctions frequently survive, *e.g.*, 12 miles north of Casterton, Victoria, the junction of a foliated granite, presumably of Archæan age, with the invaded sedimentary schists, is still perfectly sharp and transition types are apparently absent. The fact that the bulk of the dyke rock has preserved its apparent sharp junction with the grey gneiss is evidence that only special conditions will permit metamorphic diffusion. Intrusions of igneous rock into igneous, with the junctions subsequently modified by metamorphic diffusion, will necessarily be more difficult to demonstrate than igneous intrusions into sedimentary rock.

Summarising, we may assert that geological literature provides some evidence for a molecular transfer during processes of recrystallisation. It has been found a difficult matter to demonstrate, but the interpretation of the Cape Denison phenomena, with the aid of solid diffusion, is probably applicable to a number of rock junctions partially destroyed during metamorphism. If this is so a large number of unrecognised examples involving migration is indicated.

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* " The Intrusive Gneiss of Tirerrill and Drumahair," G. A. J. Cole, Proc. R.I. Acad., vol. XXIV. B, pt. 4, p. 361.

† G. A. J. Cole, Pres. Add Sect. C. Brit. Ass. Adv. Sci., Manchester, 1915, p. 5.

‡ " Geological Investigations in the Broken Hill Area," D. Mawson, Mem. Roy. Soc. S.A., vol. II., pt. 4, p. 237.

THE PROCESS OF MIGRATION.

General remarks on the problem of transference of material during metamorphism may be offered under the heads—

1. Solution.
2. Solid Diffusion.
3. Force of Crystallisation.

The remarks are confined to instances of metamorphism unaccompanied by the addition of material from any foreign source. The rocks during metamorphism have remained throughout as a solid, self-contained mass. There has been no essential change in chemical composition, and metamorphism is conceived to be merely a recrystallisation caused by super-imposed physico-chemical conditions. We also do not consider instances in which partial fusion is assumed, because we have not met with any examples in our field study.

1. *Solution.*

Solution as a transferring agent is always the factor to which there is ready appeal, and it is not easy to understand how the decrystallisation of a rock can proceed without it. There is always a measurable quantity of water ($-H_2O$) in rocks, and this is present in capillaries and hollow spaces; in addition there is the chemically combined water ($+H_2O$) which is freed at higher temperatures, and may become an active solvent. Magmatic water may also be included when finding its way to the surface for the first time. Thus there is always a minute amount of solvent present.

There is no need to enter into the discussion of conditions that assist or prevent solution. But it must be admitted here, that, provided that the metamorphic conditions are such that water can circulate, solution in some places, with corresponding deposition in other places, can be an agent in the transference of material in rocks which do not lose their rigidity. This factor is, perhaps, more noticeable in the epi zone of metamorphism which is more particularly characterised by the hydrous silicates. The presence of minute fractures is possible in this zone, and these cracks provide more ready channels of water percolation. In the production of amphibolites by the metamorphism of dolerites under epi conditions, we occasionally find microscopic veins of scapolite, lawsonite, calcite, and epidote, whose origin has been traced to large crystals of saussuritised felspar. In such cases solution has been a direct agent in the transference of material.

Microscopical solution and deposition is implied in the principle called Riecke's principle by Becke and Grubenmann. This principle is discussed by Johnston and Niggli,* who point out that it depends on the thermodynamical fact that unequal pressure, acting only on the solid phase, increases its vapour pressure and its solubility (in any particular solvent) and lowers its melting point. If a stress is applied to a rock, solution tends to occur at the points immediately under the stress with simultaneous deposition in planes at right angles. If solution occurs on the ends of a prismatic crystal, for example, and deposition occurs in the plane at right angles, the prism will be flattened first into a lenticular aggregate and finally into broad flakes. By molecular displacements in this way the rock can yield to a stress as if it were plastic, and the development of a schistose structure can be pictured with the ordinary conception of solution. If there appear new mineral forms, such as the platy minerals like biotite, which can be stable against the stress, a completely recrystallised rock may arise.

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* "General Principles Underlying Metamorphic Processes," Journ. Geol. XXI., p. 603.

2.—*Solid Diffusion.*

In many cases, however, microscopic solution cannot be so readily pictured as the means of transport, as for example, in the development of large porphyroblastic crystals in metamorphic rocks which have only been subjected to weak stress, when the pressure is mainly hydrostatic. The growth in such cases may be uniform in all directions. When a corona of garnet crystals develops during the recrystallisation of dolerites, by the reaction between felspar and augite, the garnet crystals must occupy space formerly occupied by felspar and augite; and this space is not provided by solution as in metasomatic replacement. As the garnet crystal grows it draws its supplies from adjacent regions, and in this there is a molecular transfer of material and, at the same time, a minute metamorphic differentiation. The larger the crystal grows the greater must be the distance over which it draws its supplies, and this distance must be appreciable when the garnet becomes over an inch in width. The well known secondary enlargements of hornblende, augite, plagioclase, and orthoclase which have been likened by Holland* to the growth of garnet, imply similar transfer. So also does the growth of larger crystals at the expense of the smaller crystals, with its consequent increase in grain size—a fact that is well known among the crystalline schists.†

A full discussion of the problem of solid diffusion is given by Desch in a report to the British Association for the Advancement of Science.‡ It is pointed out that the devitrification of glasses involves molecular diffusion in solids. As glassy rocks of Palæozoic age are unknown it becomes evident that solid diffusion is a process that has been operative in geological time. It is shown that diffusion in metals has been established beyond doubt. The cementation and decarburisation of iron, the segregation and recrystallisation of constituents in solid metallic alloys are processes involving true solid diffusion.

In steels the iron carbide separating from solid solution is at first in a state of ultra-microscopic division (troostite).§ On reheating and on different conditions of cooling finely granular sorbite and laminated pearlite are successively obtained. Further heating causes the pearlitic laminæ to contract, producing beaded forms and ultimately the carbide segregates into coarse masses.

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* "Origin and Growth of Garnets," T. S. Holland, Rec. G.S.I., XXIX., p. 26.

† Op. cit., Grubenmann, vol. 1, pp. 39, 78.

‡ "Report on Diffusion in Solids," C. H. Desch, Brit. A.A.S., Dundee, 1912, p. 348.

§ Troostite, Sorbite, and Pearlite are not definite compounds but aggregates of ferrite (Fe) and cementite (Fe_4C) with different structures.

The segregation of this constituent, iron carbide, in steels seems to be in some measure analogous to the segregation of chlorite in the amphibolite rocks at Cape Denison. Though the amphibolite cannot be looked upon as a solid solution, yet in each case there is the segregation of a single constituent within a solid mass. In both cases it is an adjustment of physical equilibrium, not chemical equilibrium. It is, of course, true that the segregated mass of chlorite is many times larger than the segregated mass of carbide in steel, but the former appears in the rocks of the greatest geological antiquity, while the latter is developed in a few hours in the laboratory. In the other cases of metamorphic differentiation where more than one constituent has been segregated, the analogy is still suggestive of a mental picture whereby the process can go on.

" In alloys," says the report, " which contain two solid solutions in equilibrium with one another, such as the α β alloys of copper and zinc, the structure becomes coarser when the alloys are heated at a temperature at which diffusion takes place. The increase in size of crystals is equally pronounced when only a single constituent—a pure metal or a solid solution—is present. The growth of the ferrite grains in soft steel at 700°-720° is extremely rapid, and the process can be conveniently watched in other instances. It is always the larger crystals that absorb the smaller."

" Whether the metal in which such recrystallisation takes place is homogeneous or heterogeneous, diffusion must occur in order that rearrangement may come about. The effect has been explained by the principle that small crystals have a greater solubility than large, so that if small and large crystals of the same substance are both in the presence of a solvent, solution and redeposition tend to go on until only crystals above a certain size are present. This has been verified for the case of calcium sulphate in water. A thermo-dynamical explanation has also been given of the principle that the bounding surface between a crystal and its saturated solution tends to become a minimum, so that equilibrium is only finally reached when all the small crystals have united to form a single crystal."

" The principle of differing solubility is rejected as an explanation by G. Tammann, who assumes that the surface tension, which is less than the forces producing rigidity in a crystal at the ordinary temperature, may become much more considerable with increase of temperature. When the surface tension exceeds the opposing forces, two crystals unite as two drops of fluid do. The hypothesis is applied to explain the recrystallisation of strained minerals."

This increase in grain size in metallic alloys seems to be closely analogous to the increase in grain size in certain metamorphic rocks. If solid diffusion is an operating factor in one case, it must occur in the other. At Cape Gray the first metamorphic product derived from a dolerite has a very fine granulitic structure, with average absolute grain size of 0·05mm., while localised areas of slightly coarser grains may be found. This fine-grained product has been shown to be practically identical in kind with the much coarser-grained plagioclase pyroxene gneiss at Madigan Nunatak, with average absolute grain size of 0·30mm. The differences in the grain size (1·5mm. and 0·22mm.) of the amphibolites (No. 9 and No. 629), at Cape Denison, illustrate the same phenomena. In these instances all the constituents of the rock have been uniformly enlarged. There are also cases where certain constituents are enlarged at a relatively greater rate than other constituents and heteroblastic rocks result. It is believed that the garnets in the garnet amphibolite (No. 953) have formed by the aggregation of smaller crystals, and they are uniformly larger than the average crystal of hornblende in the same rock. The large magnetite crystals in the amphibolites, Nos. 143 and 637, at Cape Denison, are also enlarged to a greater degree than neighbouring minerals, and consequently appear as porphyroblasts. An even more striking example is found in the localised variation in the size of the felspar grains that have developed in the metamorphic contact products, the biotite felspar gneisses, at Cape Denison. In three specimens from one locality the average width of the felspar crystal may vary from 0·90mm. in one case, to 8mm. in the second, and 27mm. in the third. Similar examples are known in other areas of crystalline schists and in glacier ice, and Grubenmann considers that increase in crystal size corresponds with a striving towards a condition of smallest surface tension, because the sum of free surface is decreased.

A little evidence of solid diffusion through crystalline solids and artificial crystals is given in Desch's report. But it is stated that experiments are lacking to prove the occurrence of diffusion in minerals, even under favourable conditions, though indirect evidence points to its possibility. The most favourable observations according to him are those of schiller inclusions, as of magnetite in the olivine from peridotite, Isle of Rum; and in the hypersthene from norite, Labrador; and also rutile in certain felspar and pyroxenes. These examples are phenomena connected with igneous rocks. If solid diffusion has been operative in rocks it is more likely to be traced in the rock bodies that have been completely recrystallised, without fusion, than in igneous rocks which have merely suffered slight changes on cooling after solidification. We, therefore, proceed to summarise favourable instances from our study of metamorphic rocks.

1. The presence of large porphyroblasts which have grown during the metamorphism and illustrated by—

   (*a*) Large garnets, 5cm. broad, in the garnet gneisses at Stillwell Island and Garnet Point.

   (*b*) Large felspars (oligoclase-andesine), 27mm. long, at Cape Denison, in certain metamorphic contact products, the biotite felspar gneisses.

   (*c*) Large anorthite crystals, 2½cm. wide, which are set in a fine-grained augite amphibolite found on the moraines at Cape Denison.

   (*d*) Large magnetite crystals in the amphibolites Nos. 143 and 637, at Cape Denison.

2. The variation in the crystal grain size in the same type of metamorphic rock, illustrated by—

(*a*) Plagioclase pyroxene gneisses at Cape Gray, Madigan Nunatak, and Aurora Peak, with average absolute grain sizes 0·05mm., 0·30mm., 0·17mm. respectively.

(*b*) Coarse and fine amphibolites (No. 9 and No. 629), at Cape Denison, with average absolute grain sizes 1·5mm. and 0·22mm. respectively.

(*c*) Coarse and fine biotite felspar gneisses (No. 144 and No. 146), at Cape Denison, in which the absolute size of the felspar may vary from 0·30mm. up to 27mm.

3. The existence of rocks which have been described as metamorphic differentiation products—

(*a*) Chlorite rock.

(*b*) Epidosite.

(*c*) Biotite hornblende schist.

(*d*) Bands and lenses of pure hornblende or felspar, associated with the coarse-grained amphibolites.

(*e*) The nodular zones of magnetite, sphene, and felspar in the amphibolite (No. 143).

4. The existence of the rocks which have been described as metamorphic diffusion products—

(*a*) The indefinite junction between some amphibolites and the granodiorite gneiss at Cape Denison, with the formation of hornblende and biotite gneisses.

(*b*) The apparently sharp junction between amphibolite and granodiorite gneiss illustrated in the specimen No. 372, collected from the moraines at Cape Denison, in which the amphibolite and gneiss are separated by a zone of biotite felspar gneiss 1cm. wide.

(*c*) The observed passage between some of the aplite gneisses and amphibolite at Cape Denison.

(*d*) The change of the thin threads of original basic dyke into biotite felspar gneisses at Cape Denison.

(*e*) The observed passage between cyanite garnet gneiss and amphibolite at Garnet Point.

5. In the recrystallisation of the primary augite of the basic rocks in the Cape Gray dyke series the segregation of the ilmenite involves the transmission of material through solid crystalline material.

6. The highly localised nature of the reactions which result in the formation of garnet, etc., in the garnet hypersthene felspar gneisses at the Cape Pigeon Rocks and Stillwell Island, indicate that the reactions have occurred in solid rock and the molecular supply is only provided from a very limited range.

7. The manner of change in the isomorphous mixture of plagioclase, from labradorite to andesine or oligoclase, during the reaction of labradorite with augite in the production of garnet in the garnet plagioclase pyroxene gneiss (No. 935) from Stillwell Island, indicates diffusion in the solid state.

8. The development of felspar intergrowths in metamorphic rocks, similar in character to some of the micrographic intergrowths, probably indicates solid diffusion. The intergrowths are especially abundant in the garnet hypersthene felspar gneisses at Cape Pigeon Rocks and Stillwell Island. These intergrowths bear some analogy to certain pearlitic intergrowths which have developed with conditions permitting solid diffusion. Such pearlitic intergrowths of iron carbide in phosphoferrite (solid solution of iron phosphide in iron) were produced by Stead* during the cementation of an ingot of iron containing 2 per cent. phosphorus and a little carbon. During this process a small iron core was not penetrated by the external carbon, and it gave up even the small percentage of carbon that it already had, and fan-shaped pearlitic intergrowths were produced along the junction of the altered and unaltered portions.

Though we can thus secure reason to suppose that solid diffusion can occur in crystalline minerals, we cannot find in solid diffusion the whole cause of the phenomena mentioned. In some of these cases the metamorphic diffusion products are highly schistose. This means that solid diffusion has not merely resulted in indiscriminate mixing of molecules, in the manner tending to reduce heterogeneous systems to homogeneous rocks. The operation of microscopic solution and deposition under Riecke's principle, already mentioned, helps us to picture the development of the schistosity; but there is something else involved in the production of some of the structures.

3. *Force of Crystallisation.*

In the production of the metamorphic differentiation products, such as the chlorite clot, we picture solid diffusion providing the means of molecular supply; but there is still some reason why all the chlorite molecules should converge to one centre. In the formation of the zoned nodules of felspar, sphene, and magnetite in the amphibolite No. 143, there must be some reason other than Riecke's principle why there should be such an orderly arrangement. There must be some driving force which results first in an attraction of the magnetite molecules to produce the magnetite nucleus, and secondly in an attraction of the felspar molecules to give the felspar zone. Contemporaneously there is an outward diffusion of the ferromagnesian minerals. The production of the sphene rim can be pictured, if necessary, as produced by reaction of the TiO_2 content of the magnetite with the felspar. Mere differences in rates of solid diffusion of the different constituents will not explain why felspar and magnetite have travelled in one direction while the ferro-magnesian goes in the other. The driving force which controls the direction of migration of the chlorite or of magnetite molecules we express in the term "Force of crystallisation." Stead, in the above-mentioned study on the segregatory habits of solids in alloys, recognised this driving force in the term "Crystallic attraction."

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* "The Segregatory and Migatory Habit of Solids in Alloys and in Steels below Critical Points," J. E. Stead, Journ. Soc. Chem. Ind., 1903, p. 340.

The force of crystallisation, or the power that a crystal has of drawing to itself molecules of its own kind, has been demonstrated by Becker and Day* to be, in supersaturated solutions, commensurate with the crushing strength of the rock. It is the same force which, varying in different minerals, produces the crystalloblastic order. It is, therefore, an important factor, and can be pictured as a directive agency in the recrystallisation of rocks.

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* "Linear Force of Growing Crystals," Becker and Day, Proc. Wash. Acad. Sci., vol. VII., 1905, pp. 283-288.

DESCRIPTION OF PLATES.

Plate I.

Fig. 1. Amphibolite, No. 629, Cape Denison, showing mainly hornblende and felspar. Sphene with included magnetite can be seen near the centre. Mag. 35 diam.

Fig. 2. Biotite amphibolite, No. 412, Cape Denison, showing biotite and hornblende in nearly equal proportions. Mag. 35 diam.

Fig. 3. Epidote biotite schist, No. 153, Cape Denison, showing biotite, epidote, and felspar. Sphene with included magnetite can be seen in the centre, with a crystal of hornblende a little to the left of it. Mag. 35 diam.

Fig. 4. Lawsonite amphibolite, No. 635, Cape Denison. Hornblende is the most abundant mineral and the felspar is cloudy with saussuritisation. Biotite and lawsonite are intergrown and the lobate outline of the latter can be distinguished. Mag. 35 diam.

Fig. 5. Amphibolite, No. 628·6, with a vein of lawsonite, Cape Denison. The walls of the vein are lined with epidote. Mag. 35 diam.

Fig. 6. Lawsonite amphibolite, No. 720, Cape Denison. Hornblende is the most abundant constituent and the felspar is cloudy. The lawsonite is colourless, with good cleavage, and in large crystals, and it may be seen bending against the hornblende and extending across the field. Mag. 35 diam.

Plate II.

Fig. 1. The junction of a meta-xenolith of gneiss with the amphibolite, Cape Denison. The xenolith, the colourless portion, consists of a granular aggregate of quartz and felspar. Mag. 35 diam.

Fig. 2. The same field as the preceding, in polarised light, and the granulitic aggregate of quartz and felspar forming the xenolith is apparent. Mag. 35 diam.

Fig. 3. A large relic crystal of quartz in a meta-xenolith of gneiss. The early stages of the granulitisation can be seen at the extremity of the large crystal. X nicols. Mag. 45 diam.

Fig. 4. The junction of a meta-xenolith of saussurite with the amphibolite. The boundary of the primary felspar has been preserved in this example. Large crystals of epidote are set in the saussuritic aggregate. Mag. 35 diam.

Fig. 5. Epidosite, No. 415, Cape Denison, showing epidote and felspar. The dark mineral in the upper half is sphene, and a crystal of hornblende is situated in the left centre. It occurs as a clot in the amphibolite, No. 628. Mag. 35 diam.

Fig. 6. Biotite hornblende schist, No. 4, Cape Denison, showing long prisms of hornblende intergrown with biotite. This rock occurs as a clot in the amphibolite bands. Mag. 35 diam.

PLATE III.

Fig. 1. Diablastic structure, or a secondary intergrowth of quartz and felspar in the hypersthene alkali felspar gneiss at Madigan Nunatak. X nicols. Mag. 35 diam.

Fig. 2. A similar, but much finer, diablastic intergrowth in the same slide as Fig. 1. Mortar structure is seen and the intergrowth has developed in the crush area. X nicols. Mag. 35 diam.

Fig. 3. Hypersthene alkali felspar gneiss, No. 949, Stillwell Island. It is a rock similar to " charnockite " and occurs in dyke form. Mag. 35 diam.

Fig. 4. Garnet cordierite gneiss, Cape Gray, showing the finely granulitic character of the cordierite. The large clear crystal at the top is quartz. X nicols. Mag. 35 diam.

Fig. 5. This and the following illustrate a slide cut across the junction of the cyanite biotite gneiss with the amphibolite at Garnet Point, No. 781. This figure illustrates the hornblende part of the slide. The dark mineral is hornblende, and the colourless mineral with which it is intergrown is cyanite. Mag. 35 diam.

Fig. 6. The biotite part of the slide, No. 781. The dark mineral is biotite, and the mineral with high refractive index is garnet. The colourless portion consists of cyanite and quartz chiefly. Mag. 35 diam.

PLATE IV.

Fig. 1. Plagioclase pyroxene gneiss, No. 794, Madigan Nunatak. Plagioclase, pyroxene, and ilmenite with a very little hornblende are visible. The narrow granulated selvages around the pyroxene crystals can be detected in part. The rock has practically the same percentage mineral composition as No. 773 (Plate VI., fig. 5). Mag. 35 diam.

Fig. 2. Hornblende plagioclase pyroxene gneiss, No. 759, Aurora Peak. The darker hornblende is readily distinguished from the pyroxene on the one hand and from the ilmenite on the other. The rock has practically the same mineral composition as No. 794, Fig. 1, except that part of the pyroxene is replaced by hornblende. Mag. 35 diam.

Fig. 3. Garnet hypersthene felspar gneiss, No. 785 (2), Cape Pigeon Rocks. A crystal of ilmenite is surrounded by a zone of biotite and quartz. A little ilmenite and garnet are scattered through the zone which extends as a bight into a large hypersthene crystal on the left and top of the figure. Mag. 45 diam.

Fig. 4. Garnet hypersthene felspar gneiss, No. 785 (3), Cape Pigeon Rocks, showing an association of biotite and hypersthene. A garnet fringe is present between the biotite and felspar. The biotite has in part developed a perforated appearance, and a portion of the flake is bent. Mag. 35 diam.

Fig. 5. Garnet hypersthene felspar gneiss, No. 785 (2), Cape Pigeon Rocks, showing the intergrowths of felspars and quartz in polarised light. Mag. 45 diam.

Fig. 6. The same slide as Fig. 5, showing the relation of myrmikoidal felspar intergrowth with the biotite. The lower right consists of biotite sprays and a thin lath of biotite is seen as a dark line from which the felspar vermiculæ radiate. Other intergrowths appear as the stage is rotated. A crystal of microcline is situated in the top left hand corner. X nicols. Mag. 65 diam.

PLATE V.

Fig. 1. Garnet rims surrounding aggregates of biotite and quartz in the hypersthene felspar gneiss, No. 785 (2), Cape Pigeon Rocks. A fragment of hypersthene remains on one side of the aggregate. Mag. 45 diam.

Fig. 2. A crystal of hypersthene surrounded by biotite and an outer garnet rim in the same slide as Fig. 1. Mag. 45 diam.

Fig. 3. Sprays of biotite issuing from an ilmenite nucleus in the hypersthene felspar gneiss, No. 979 (2), Stillwell Island. Mag. 35 diam.

Fig. 4. The same field as Fig. 3 in polarised light showing the manner in which some of the sprays open out into felspar intergrowths. Mag. 35 diam.

Fig. 5. Hypersthene alkali felspar gneiss, No. 947, Stillwell Island. The slide is cut from the garnetiferous portion of the specimen. Biotite, with a rim of garnet, is seen in the upper portion. Garnet, with inclusions of ilmenite, is a little lower on the right, and pyroxene appears on the lower left. Mag. 35 diam.

Fig. 6. The garnet rims around ilmenite in the same slide as Fig. 5. One crystal of ilmenite has been partly torn out of the slide in the grinding. Mag. 35 diam.

PLATE VI.

Fig. 1. A crystal of ilmenite surrounded by biotite and an outer garnet rim in the hypersthene felspar gneiss from the Cape Pigeon Rocks, No. 785 (2). Mag. 45 diam.

Fig. 2. The serpentine-hypersthene aggregate in the hypersthene felspar gneiss, No. 785 (3), from the Cape Pigeon Rocks. The crystals of hypersthene are partly altered to serpentine and are outlined by seams of garnet. A pleochroic halo is seen in the lower right. Mag. 35 diam.

Fig. 3. The garnet rim around the biotite is broken by the development of a spray of secondary biotite which opens out into the usual vermicular intergrowths of felspar, but these are not visible in ordinary light. A certain amount of the secondary biotite also appears on the outside of the garnet rim. Hypersthene felspar gneiss, No. 785 (2), Cape Pigeon Rocks. Mag. 35 diam.

Fig. 4. A flake of basal biotite is surrounded by a rim of younger biotite and quartz. Hypersthene felspar gneiss, No. 979 (2), Stillwell Island. Mag. 45 diam.

Fig. 5. Plagioclase pyroxene gneiss, No. 773, Cape Gray, showing chiefly a fine-grained aggregate of pyroxene and felspar with scattered ilmenite. The outlines of the felspar laths of the primary dolerite can be plainly detected. The rock has the same percentage mineral composition as No. 794 (Plate IV., fig. 1). Mag. 35 diam.

Fig. 6. The same field as Fig. 5 in polarised light. The primary felspar laths are converted into granulitic aggregates of secondary felspar. Mag. 35 diam.

PLATE VII.

Fig. 1. Hornblende plagioclase pyroxene gneiss, No. 766, Cape Gray. The schistose character is seen, and the dark hornblende is distinct from the paler pyroxene. A plate of relic pyroxene is seen partly altered to the fine granulitic aggregate of secondary pyroxene and hornblende. Mag. 35 diam.

Fig. 2. Garnet plagioclase pyroxene gneiss, No. 935, Stillwell Island. The field is occupied by a large crystal of relic pyroxene which is darkened by numerous minute crystals of ilmenite. On the left and extreme right the relic pyroxene is replaced by granulitic aggregates of clear secondary pyroxene with the partial coalescence of the minute ilmenites. The relic pyroxene is also partly replaced by granulitic aggregates of hornblende which surround an ilmenite nucleus. Mag. 45 diam.

Fig. 3. Garnet amphibolite, No. 799, Garnet Point. Note the manner in which the garnet crystal is set in a felspar base. Mag. 35 diam.

Fig. 4. Amphibolite, No. 781, Garnet Point. This is the amphibolite which junctions the cyanite biotite gneiss in Plate III., figs. 1 and 2. Mag. 35 diam.

Fig. 5. Plagioclase pyroxene gneiss, No. 951, Stillwell Island. The crystals of biotite and pyroxene are surrounded by a diablastic intergrowth of pyroxene and felspar. This pyroxene is partly granular and partly vermicular, and is interpreted as the first stage in the production of garnet. Mag. 35 diam.

Fig. 6. Hornblende plagioclase pyroxene gneiss, No. 942, Stillwell Island. The centre is a roughly circular area of diablastic pyroxene and felspar which is partly surrounded by hornblende and biotite. In the lower part of the photograph the larger granular pyroxene is seen. Mag. 35 diam.

PLATE VIII.

Fig. 1. Garnet amphibolite, No. 953, Stillwell Island. The large garnet is penetrated by an area of vermicular pyroxene and felspar. It appears as if a portion of the garnet crystal has broken up into the pyroxene and felspar, but this is not the general case. Mag. 35 diam.

Fig. 2. Garnet amphibolite, No. 953, Stillwell Island. The pyroxene vermiculæ are set radially to an ilmenite nucleus and are partially enclosed by the garnet. The crystals of ilmenite have been set in secondary pyroxene which has partly reacted with the felspar to produce garnet while the residue now appears as vermiculæ. Mag. 35 diam.

Fig. 3. Garnet amphibolite, No. 953, Stillwell Island. The same phenomena as in Fig. 2 appears enclosed within a garnet crystal, but it has the same origin. This example only differs from Fig. 1 in the presence of the ilmenite, and hence it is not necessary to assume the decomposition of the garnet in Fig. 1. The large garnets are due to growth at the expense of the smaller garnet crystals, and, like all crystals in recrystallised rocks, may include all other constituents. The fact of inclusion has little significance. Mag. 35 diam.

Fig. 4. Garnet plagioclase pyroxene gneiss, No. 935, Stillwell Island. The centre of the field is occupied by a granulitic mass of secondary pyroxene, and this is surrounded by a garnet rim, produced by the interaction between pyroxene and felspar. Mag. 35 diam.

Fig. 5. Another field in the same slide as Fig. 4. The nucleus of granular pyroxene is much smaller. Mag. 35 diam.

Fig. 6. Almost the same field as in Fig. 5 in polarised light. The garnet is black and the granulitic character of the pyroxene is noticeable. The manner of the change in the composition of the felspar, concurrent with the formation of the garnet, is seen. The outer rim of the felspar crystal, together with the "graphic" inclusions, have a smaller angle of extinction than the bulk of the crystal. Mag. 45 diam.

PLATE IX.

Figs. 1, 2, and 3. These are different examples of the composite type of metamorphosed xenoliths composed of saussurite and hornblende, from Cape Denison. The saussurite marks the junction with the enclosing amphibolite. Fig. 2 shows a remarkably angular xenolith. The crystal boundaries of the primary felspar in the primary aggregate can be distinguished in Fig. 3. The specimens in Figs. 2 and 3 were not found *in situ* though very close to the actual outcrop of the xenoliths. Similar specimens were found *in situ* and are in the collection, but the pebbles make excellent diagrams.

Fig. 4. This is also a diagrammatic specimen, obtained from the "lower moraine," at Cape Denison, close to the *in situ* occurrence. It is an amphibolite dotted with pieces of saussurite of varying sizes.

Fig. 5. Specimen of augite amphibolite found on the moraines at Cape Denison. It contains a large porphyroblast of anorthite (Ab_1 An_8). These crystals are tinted dark green and are perfectly clear and are a product of the recrystallisation.

Fig. 6. Specimen of biotite amphibolite, No. 143, collected from an enclosed basic patch in the gneiss at Cape Denison. It contains small nodular crystals of magnetite surrounded by a felspar zone, which passes out into normal amphibolite. Each nodule is looked upon as a metamorphic differentiation centre.

PLATE X.

Fig. 1. Metamorphosed gneissic xenolith embedded in amphibolite. The xenoliths are drawn out into an elongated oval form in the direction of the schistosity. Collected *in situ* in the amphibolite band, No. 629, at Cape Denison.

Fig. 2. Side view of the specimen in Fig. 1. In section the angular shape of these gneissic xenoliths can be seen, and the schistosity of the rock passes through them irrespective of its outline.

Fig. 3. This is a more massive specimen than that in Figs. 1 or 2. Note the irregular outline of the metamorphosed gneissic xenoliths. The outline of at least two of these has been rendered indefinite during the recrystallisation. Collected *in situ,* Cape Denison.

Fig. 4. The reverse view of the specimen in Fig. 3. The sharp angular outline of a xenolith can be seen near the bottom left hand corner. In this specimen there are xenoliths both with sharp boundaries and without sharp boundaries. This rapid variation renders it unlikely that the xenoliths were partially absorbed by the dyke magma before its primary consolidation.

Fig. 5. A remarkably angular xenolith consisting of almost pure saussurite. The boundary is perfectly sharp and definite, except for a very small length in the bottom left hand corner. Collected *in situ,* Cape Denison.

Fig. 6. A saussurite xenolith in which the re-entrant angle of the primary felspar twin is retained. Collected *in situ,* Cape Denison.

PLATE XI.

Fig. 1. Composite gneiss from Cape Denison in which threads of quartz felspar veins laminate the darker gneiss. The original boundaries are now indefinite.

Fig. 2. Specimen of granodiorite gneiss with an excessively contorted vein, Cape Denison.

Fig. 3. Specimen of hornblende gneiss which has been fractured by frost. It was collected from the moraines at Cape Denison, and the two halves of the boulder were found lying within a few feet of one another. The fracture plane does not correspond with the direction of the schistosity.

Fig. 4. Specimen of granodiorite gneiss showing curved foliation planes. Collected *in situ* from Cape Denison.

Fig. 5. Specimen of granodiorite gneiss showing a banded character, Cape Denison.

Fig. 6. Specimen of aplitic gneiss showing a large crystal of allanite. Collected *in situ*, Cape Denison.

PLATE XII.

Figs. 1, 2, 3, are photographs of biotite felspar gneiss, Nos. 144, 146·1, 146·2, of similar composition. Collected from within a few feet of one another at Cape Denison. The porphyritic character is a metamorphic variation, and has nothing to do with the original character of the rocks, because these rocks are considered to be metamorphic hybrids.

Fig. 4. Specimen showing a thread of grey gneiss between two portions of dark biotite felspar gneiss, No. 145. The boundary on either side of the grey gneiss is indefinite as a result of metamorphic diffusion.

Fig. 5. Specimen No. 372, collected from the moraines at Cape Denison. The apparent sharp junction between the dark amphibolite and the grey granodiorite gneiss is seen. Actually there is a transition and a zone of biotite felspar gneiss separates the two.

Fig. 6. Specimen of hornblende gneiss from the moraines at Cape Denison. It contains a dark band of amphibolite and shows the normal sharp junction of the amphibolite bands and the granodiorite gneiss at Cape Denison.

PLATE XIII.

Fig. 1. External, weathered surface of beach rock (No. 702), Cape Denison. X $\frac{4}{3}$.

Fig. 2. Cut surface of ditto, showing the cavernous and detrital nature of the rock. X $\frac{4}{3}$.

Fig. 3. Thin section of the rock, showing angular sand-grains and fine calcareous and detrital cement. X 21.

Fig. 4. Part of thin section passing through the coral fragment. X 21.

PLATE XIV.

Fig. 1. The junction of the rocky cliffs at Cape Denison and the ice cliffs of Commonwealth Bay at "Land's End."

Fig. 2. The lower part of the glacier wall at John o' Groats, where it rests on a rocky floor below sea level, and where it is darkened by inclusions of rock detritus. The curved lines are big conchoidal fractures which are probably connected with the presence of a steep rock wall immediately on the right of it. Pancake ice in the foreground.

PLATE XV.

Fig. 1. The ridges are crowned with numerous small peaks and possess the character of a miniature mountain range. Cape Denison.

Fig. 2. The narrowest valley at Cape Denison. The rough surface has been caused by frost action.

PLATE XVI.

Fig. 1. A band of epidote biotite schist (No. 153) which has been more resistant to weathering than the surrounding granodiorite gneiss. The reverse is usually the case at Cape Denison.

Fig. 2. A steep wall of granodiorite gneiss at Cape Denison with a black amphibolite band at the base.

PLATE XVII.

Fig. 1. The northern end of Lake II. which is nearly frozen over. The furrowed and encrusting character of the lake ice is due to freezing during agitation by the winds. Skua gulls are bathing on the edge of the water.

Fig. 2. The broad valley in which the hut was situated at Cape Denison. The photograph was taken while low surface drift was sweeping down the valley. The surface drift produces the haziness over portions of the rocks. The feet of the figure on the right are invisible for the same reason.

PLATE XVIII.

Fig. 1. Highly polished rock which is characteristic of the peripheral area below the 40ft. contour level at Cape Denison.

Fig. 2. A glacial pavement. A portion of a block about 9ft. square with well marked parallel striæ trending N. 32° E. at Cape Denison.

PLATE XIX.

Fig. 1. The " wave-sorted moraine " or " lower moraine " at Cape Denison, showing a collection of large rounded boulders.

Fig. 2. A large boulder of silicated limestone found on the moraine at Cape Denison. It has probably not been carried far. A parallel set of ice striæ can be seen on the

boulder trending across the schistosity. The parallelism of these striæ indicate that they were probably received before the rock was plucked out of its *in situ* position by the onward travel of the glacier.

PLATE XX.

Fig. 1. View across the most easterly valley on Cape Denison. Lake V. can be seen on the floor of the valley.

Fig. 2. View of Lake IV., looking south towards the glacier slopes. Beyond the lake a moraine bar is visible. Still further on the upper limit of the discoloured ice is marked by the upper limit of the white snow.

Fig. 3. Highly contorted granodiorite gneiss at Cape Denison.

Fig. 4. Rock surface disturbed by frost action. It occupies a position where the drainage of the thaw water is retarded.

PLATE XXI.

Fig. 1. Jointing in the granodiorite gneiss, Cape Denison.

Fig. 2. View looking down the glacier slopes towards Lake IV. The moraine bank is more prominent than in Plate XX., fig. 2. The north bank of the lake in the distance can be seen to be thickly covered with morainic material, shown in greater detail in Plate XXIII., fig. 1.

PLATE XXII.

Fig. 1. View showing three parallel amphibolite bands at Cape Denison. The place is situated above the 40ft. contour level, and the surface is very rough compared with that in Fig. 2.

Fig. 2. View illustrating the surface below the 40ft. contour level. Note the smoothed and polished appearance. Two dark basic schlieren can be seen.

PLATE XXIII.

Fig. 1. Glacial detritus thickly strewn along the rocky bank of a small glacial lake.

Fig. 2. An erratic on the moraine at Cape Denison.

PLATE XXIV.

Fig. 1. The Madigan Nunatak from the south-east.

Fig. 2. The Madigan Nunatak from the south-west.

Fig. 3. Cape Gray from the edge of the barrier ice cliffs, looking north-west. The gully-way which divides the island is visible. It is formed by a large metamorphosed basic dyke.

Fig. 4. View from the barrier ice cliffs near Cape Gray, showing various members of the Way Archipelago. A large amount of heavy floe ice is visible. This ice had accumulated between the islands of the Way Archipelago and broken out before the arrival of the sledge party on December 16th, 1912.

PLATE XXV.

Fig. 1. View from the eastern side of the Cape Gray Promontory, looking north-east out of Watt Bay. Four individuals of the Way Archipelago can be seen, including a very curious, wedge-shaped island.

Fig. 2. Crumpled gneiss at the Cape Pigeon Rocks.

Fig. 3. View from Garnet Point, looking north-east out of Watt Bay. A steeply conical member of the Way Archipelago can be seen. Penguins are inspecting a mitten in the foreground.

Fig. 4. The steep descent to Garnet Point. An ice ramp enabled the sledge party to descend from the top of the barrier cliff down to the rock exposure.

PLATE XXVI.

Figs. 1 and 2. These are two views showing the large aggregates of garnet and biotite in the garnet felspar gneiss at Garnet Point. The ice axe, in Fig. 1, is 36in. long, 10½in. wide at the pick end, and the handle is 1½in. in diameter.

Fig. 3. Aurora Peak.

Fig. 4. A close view of a narrow recrystallised basic dyke at the Cape Pigeon Rocks.

PLATE XXVII.

Fig. 1. The large recrystallised basic dyke cutting the garnet gneiss on the northern part of the Cape Pigeon Rocks. An offshoot can be seen in the photograph. Specimen No. 767 was collected from the large dyke.

Fig. 2. A recrystallised basic dyke at Cape Gray. It cuts the garnet cordierite gneiss and a fine stringer can be seen branching out into the gneiss on the right hand side.

Fig. 3. The foliation anticline at the southern end of the Madigan Nunatak.

Fig. 4. The large recrystallised basic dyke on the southern half of the Cape Pigeon Rocks. The view is taken from the northern part.

PLATE XXVIII.

Panorama of the northern half of the Cape Pigeon Rocks.

PLATE XXIX.

Stillwell Island, one of the largest members of the Way Archipelago.

PLATE XXX.

Fig. 1. A panorama looking across Cape Denison. On the left and in the distance are the rising slopes of the inland ice. The moraine is in the foreground.

Fig. 2. A panorama of the sea front looking eastward from Cape Denison. A stretch of waterworn boulders is seen on the right, which are part of the beach deposits which are referred to as the "lower moraines." The plateau slopes are visible to a height of about 1,500ft.

PLATE XXXI.

Fig. 1. A panoramic view looking south from near the hut. In the distance are the slopes of the inland ice sheet. In the foreground is the terminal moraine. Between the rocks and the figure is a zone of ice impregnated with detritus which causes rapid thawing on calm summer days.

Fig. 2. A panoramic view looking north towards the sea. In the middle of the picture is Round Lake.

PLATE XXXII.

The Mackellar Islets viewed from an elevation of 800ft. on the mainland.

PLATE XXXIII.

Fig. 1. A large island of the Mackellar group, showing its planated surface. Colonies of Adelie penguins are distributed over it, and the rocks in the foreground are encrusted with salt.

Fig. 2. Cape Hunter, composed of phyllites with vertical cleavage planes.

PLATE XXXIV.

Locality map of Adelie Land.

PLATE XXXV.

Locality map of Cape Denison.

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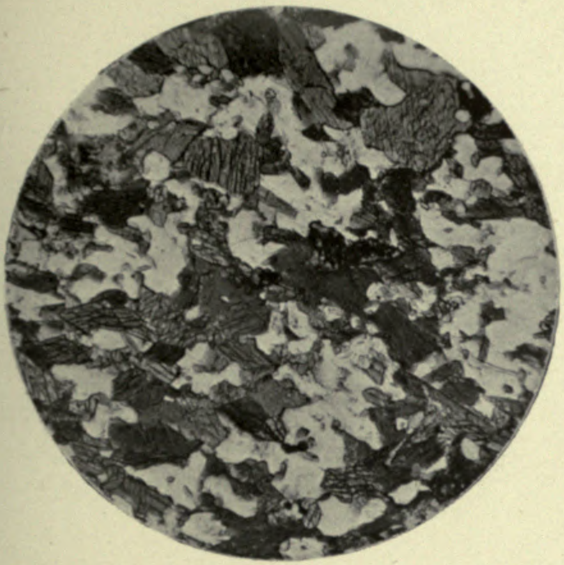
PLATE I.



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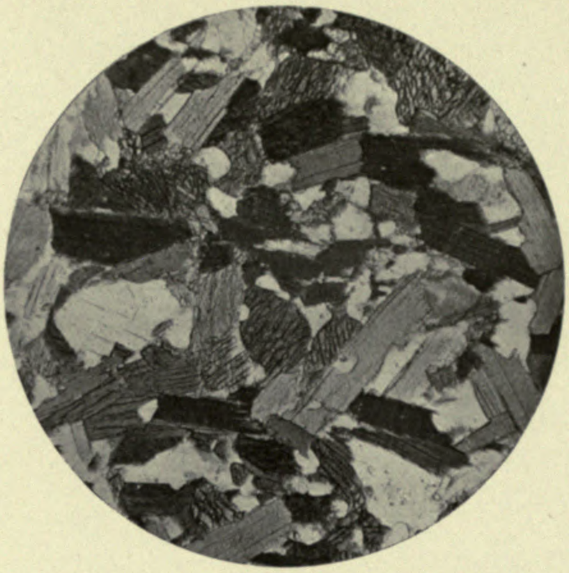

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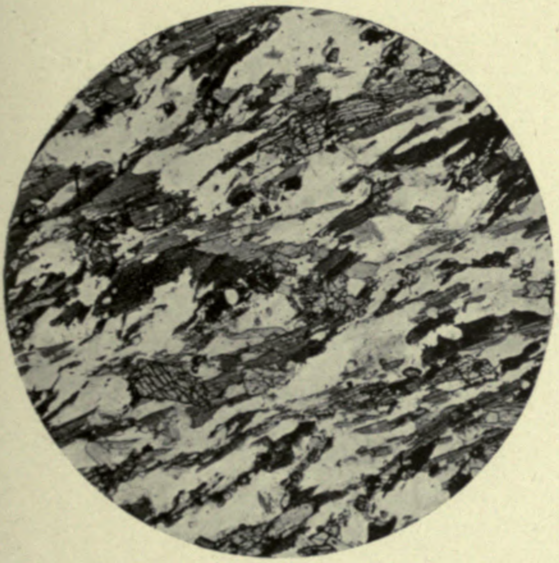

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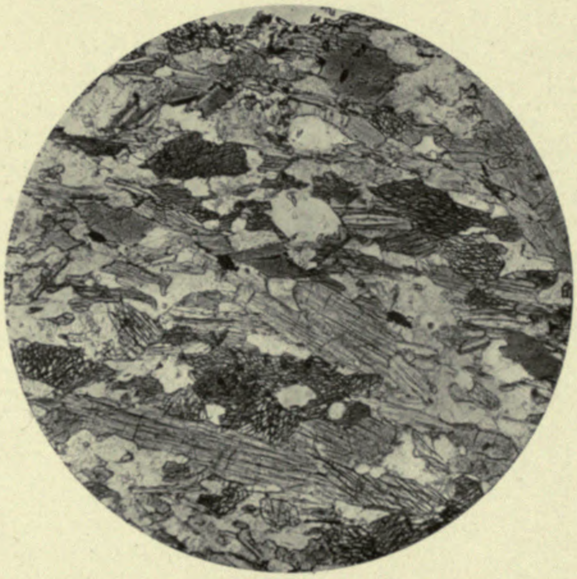

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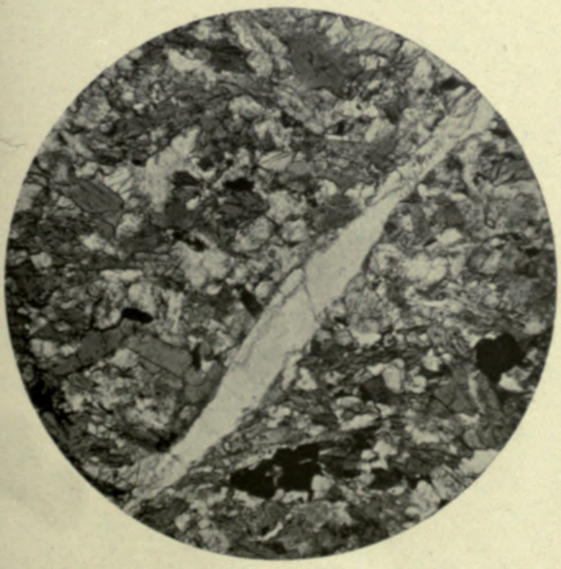

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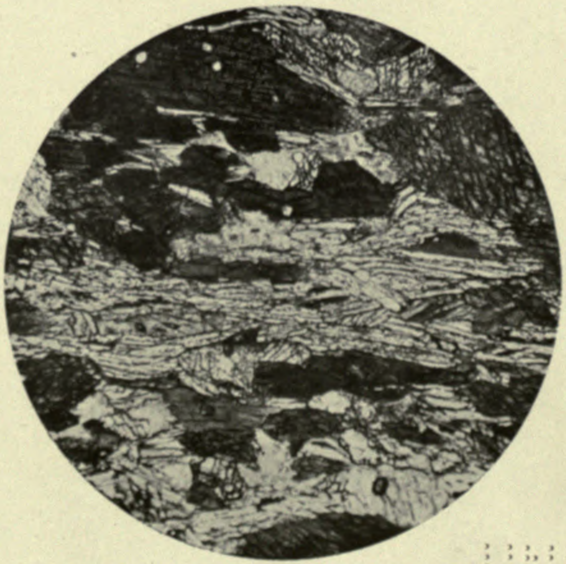

Fig. 6. *Stillwell.*

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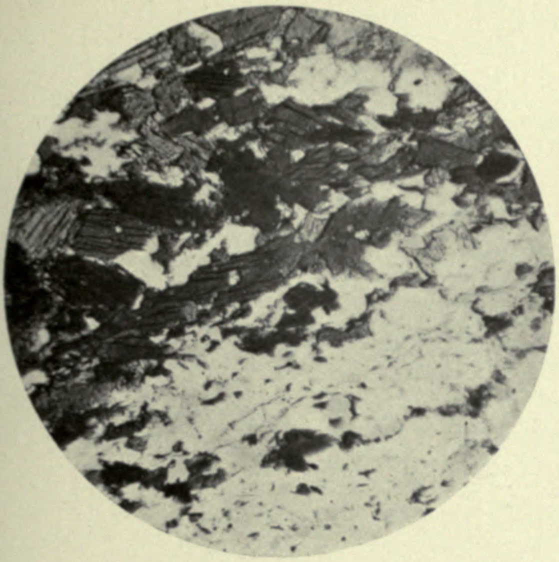

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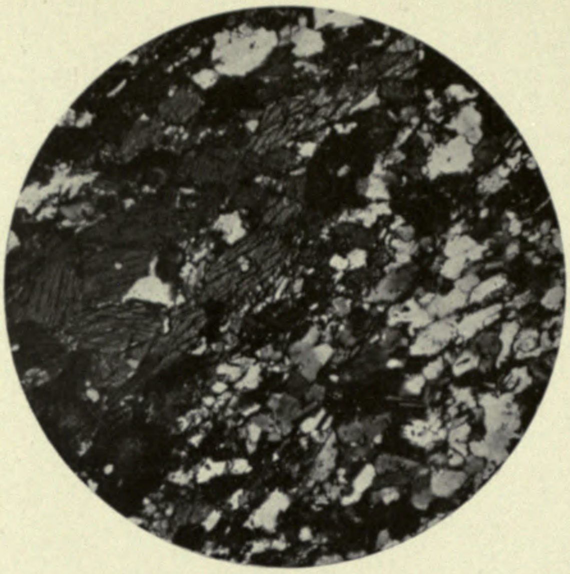

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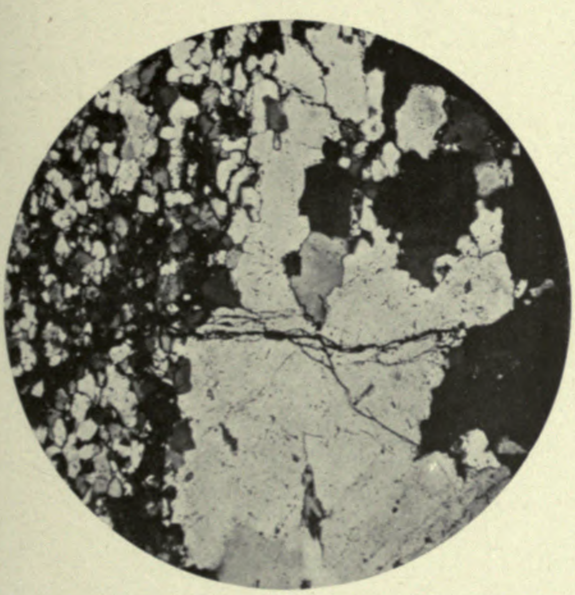

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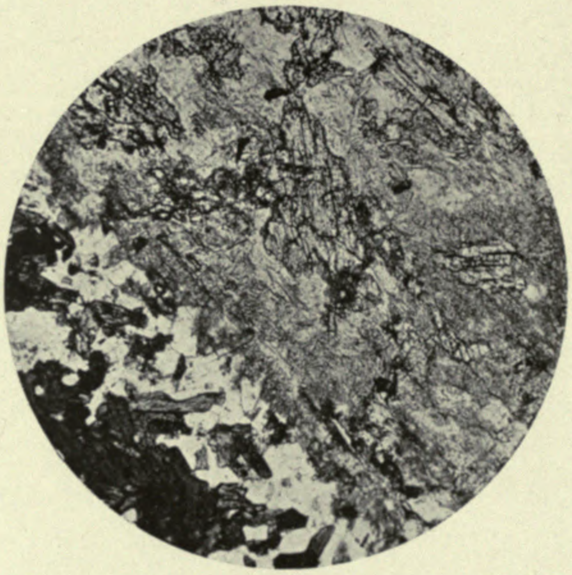

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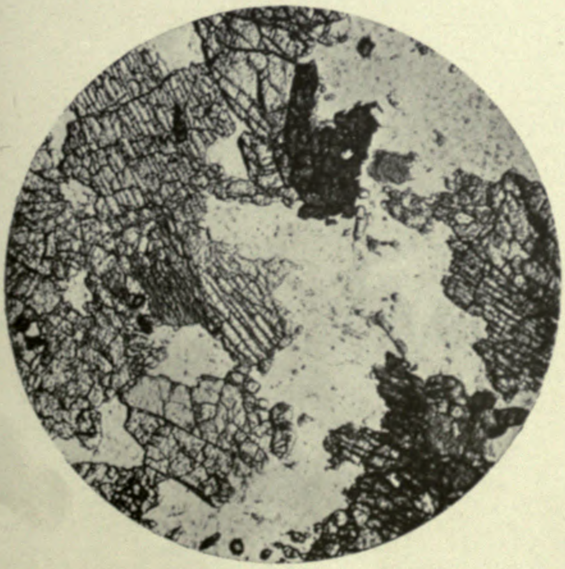

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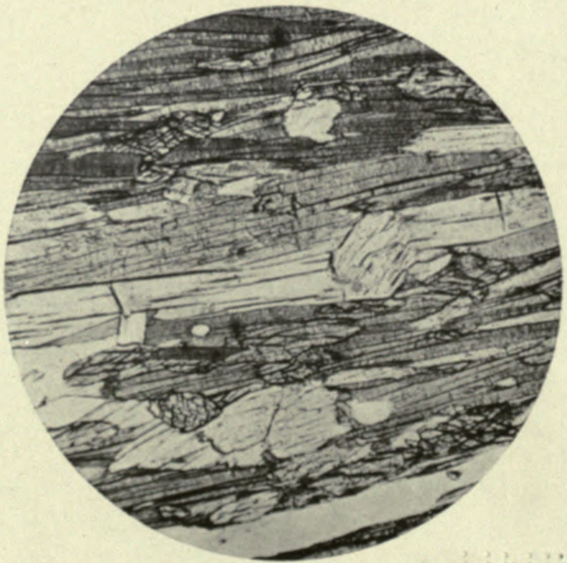

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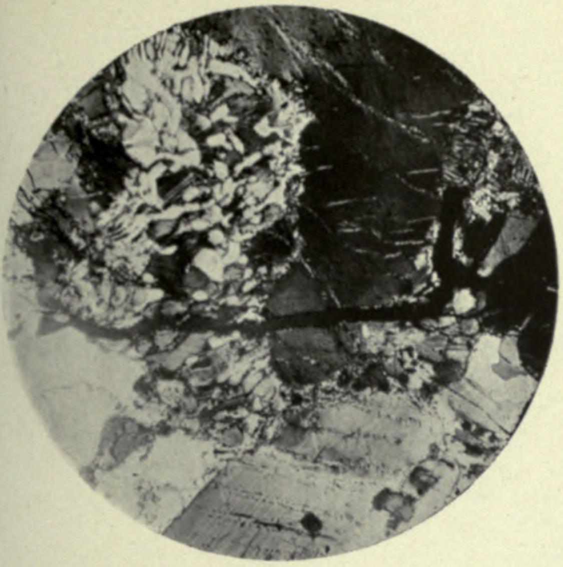

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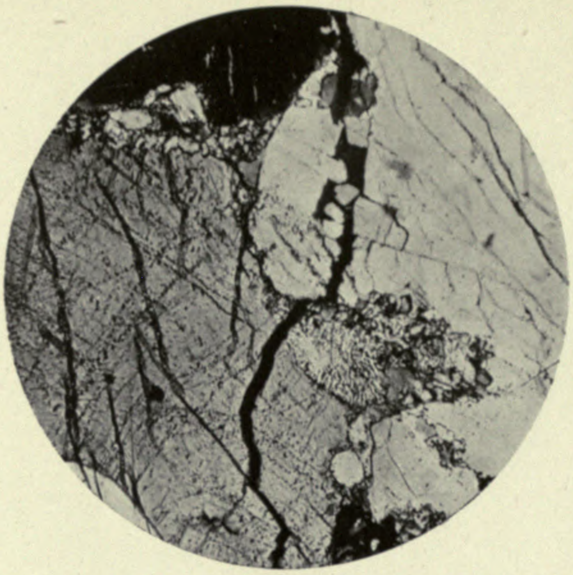

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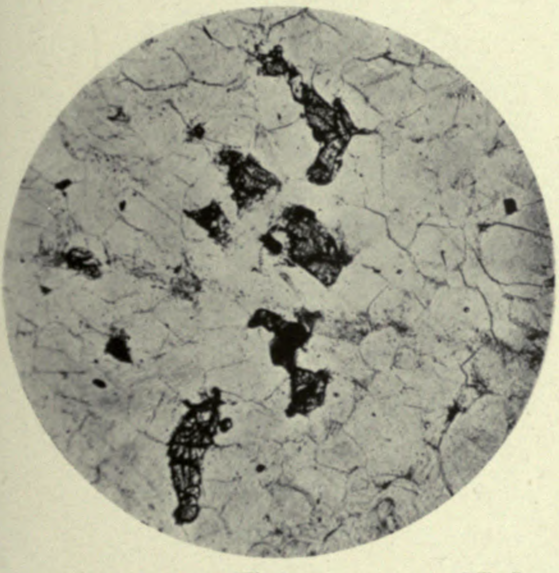

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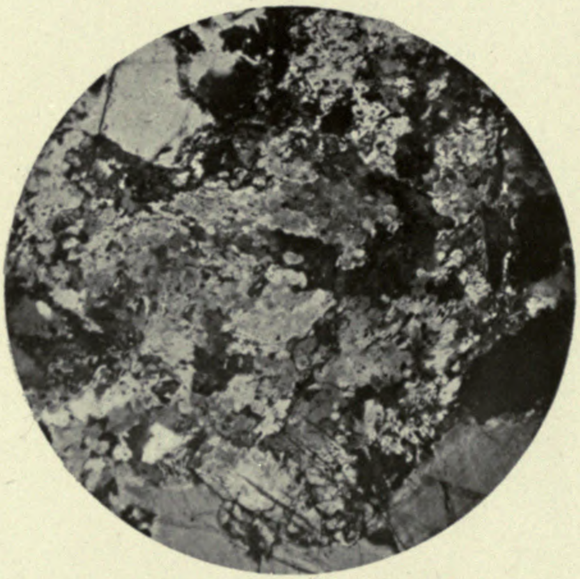

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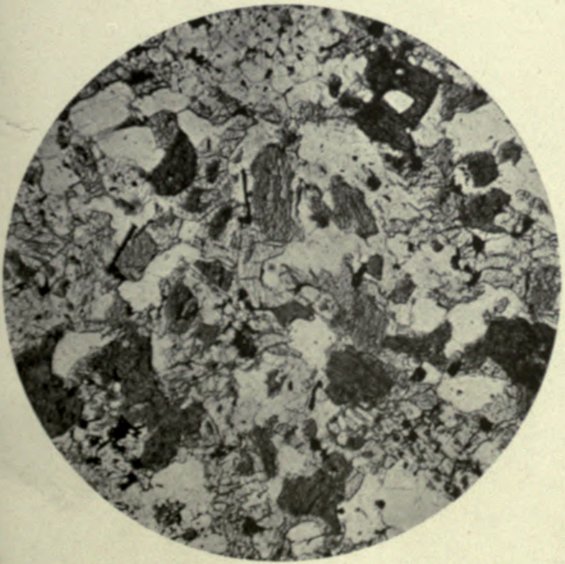

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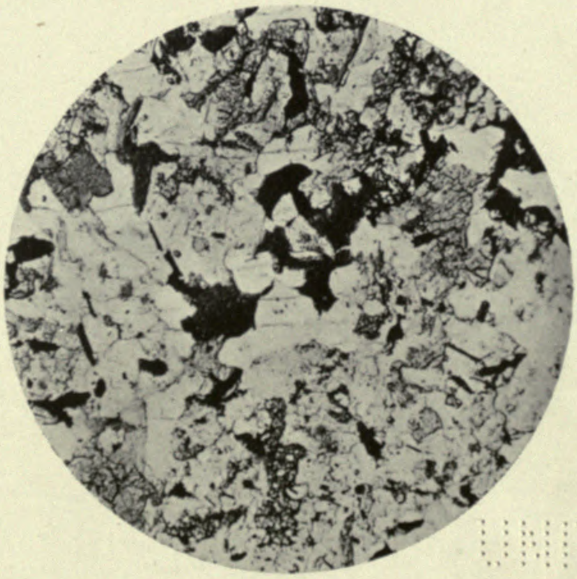

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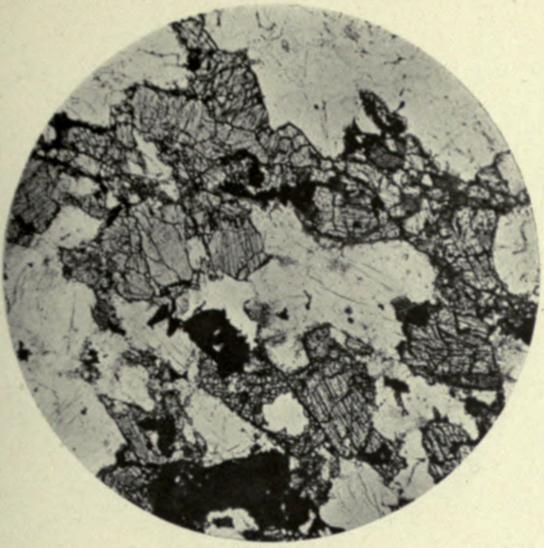
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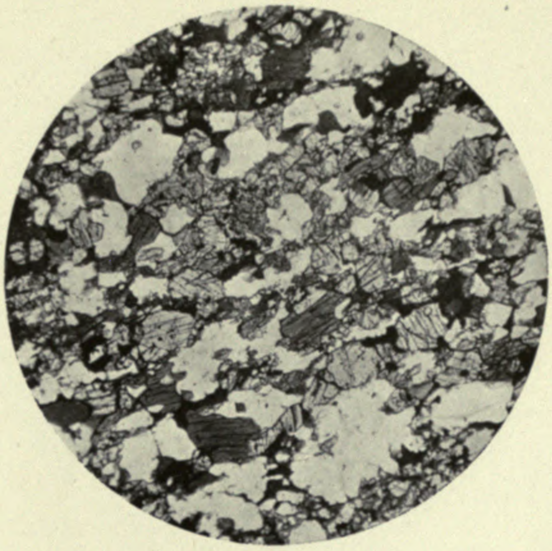
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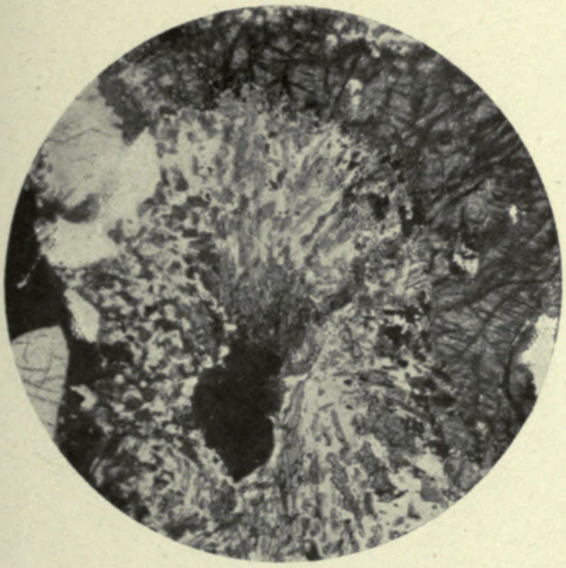
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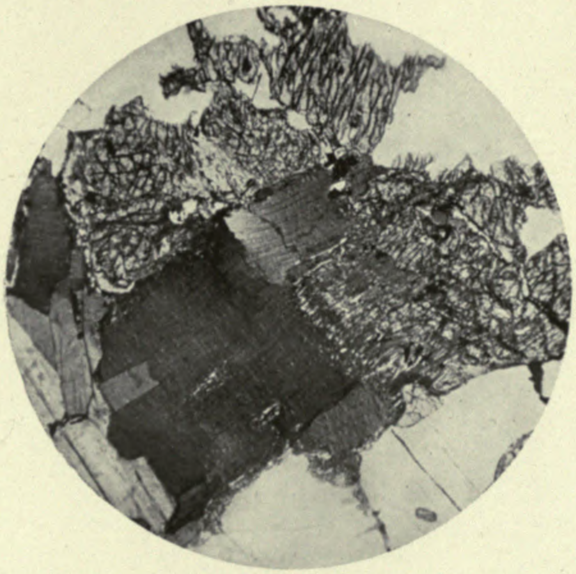
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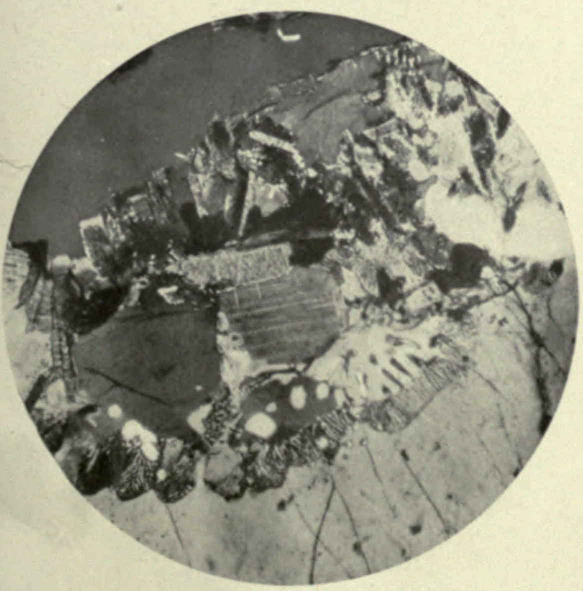
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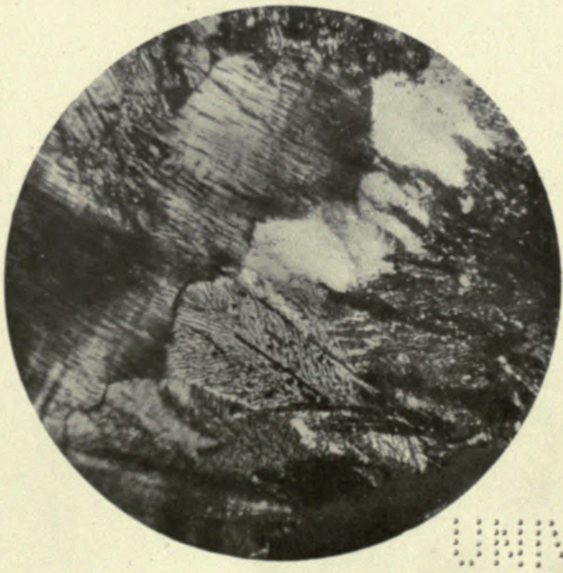
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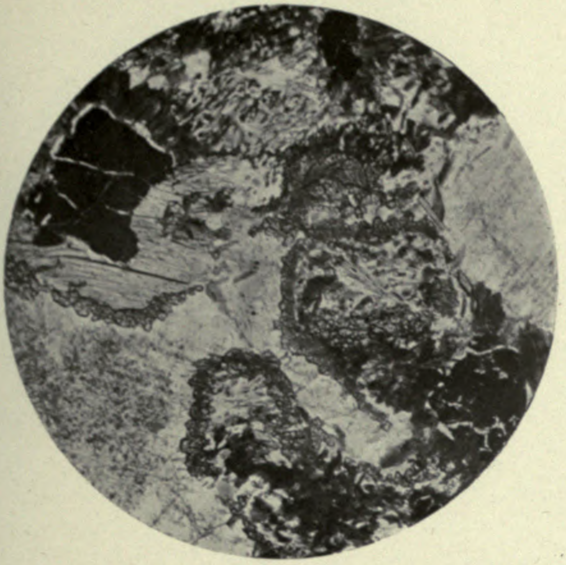

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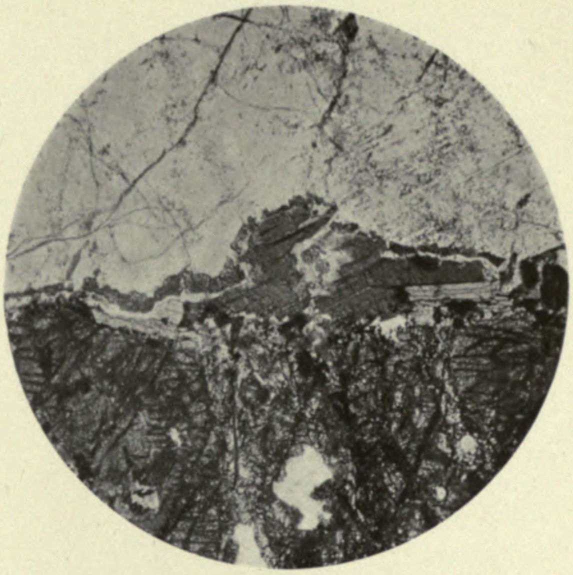

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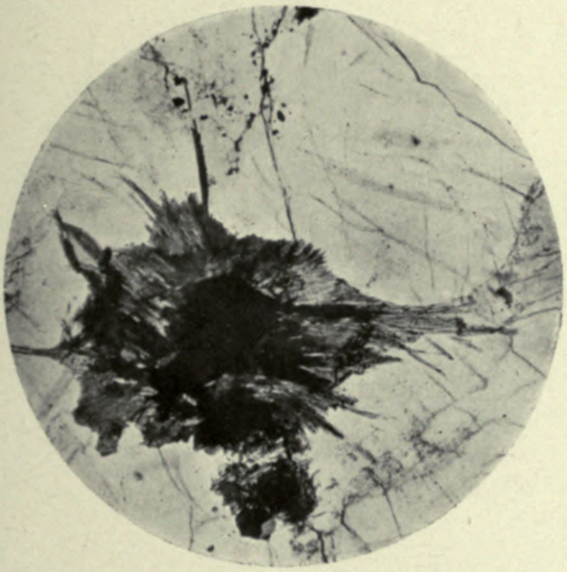

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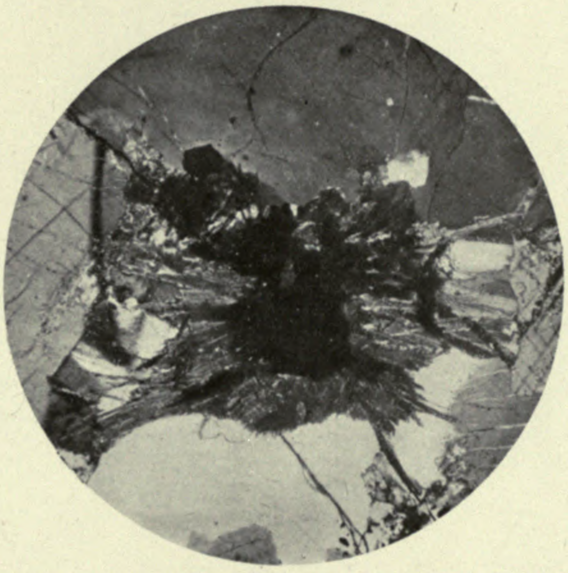

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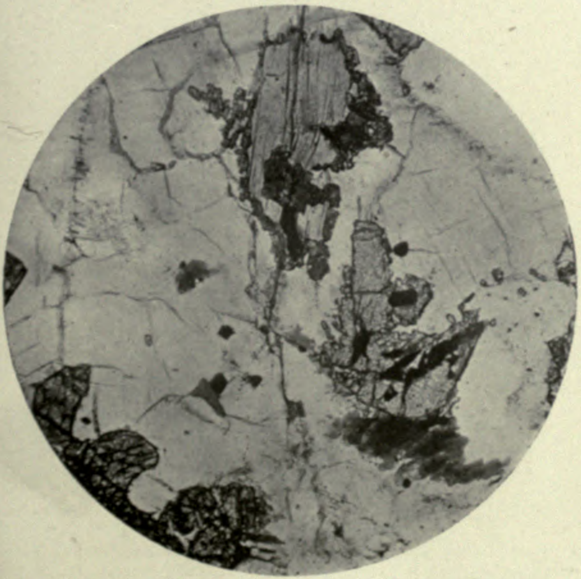

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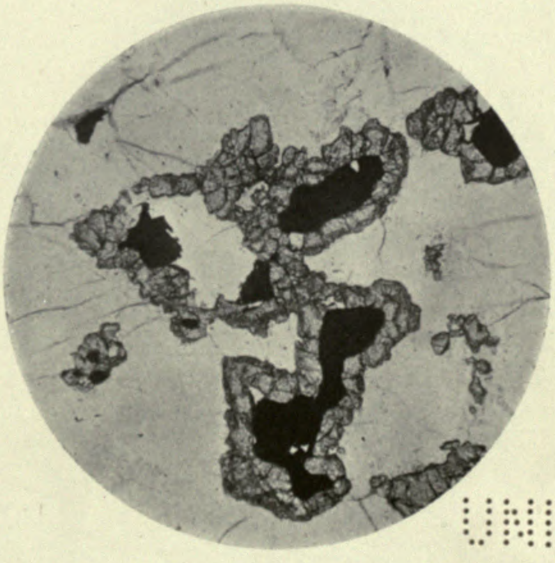

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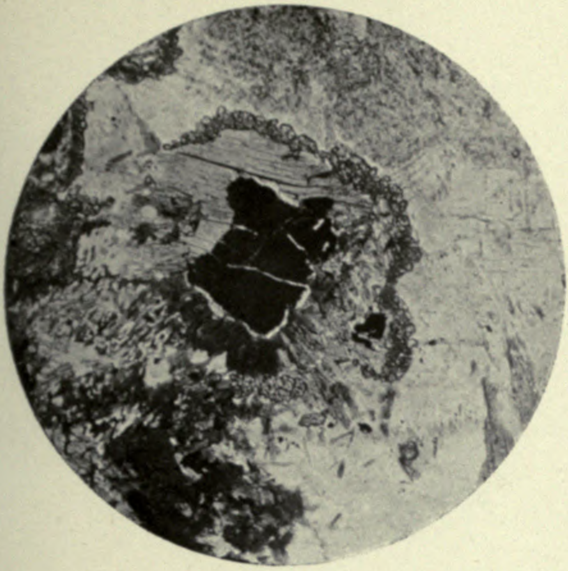
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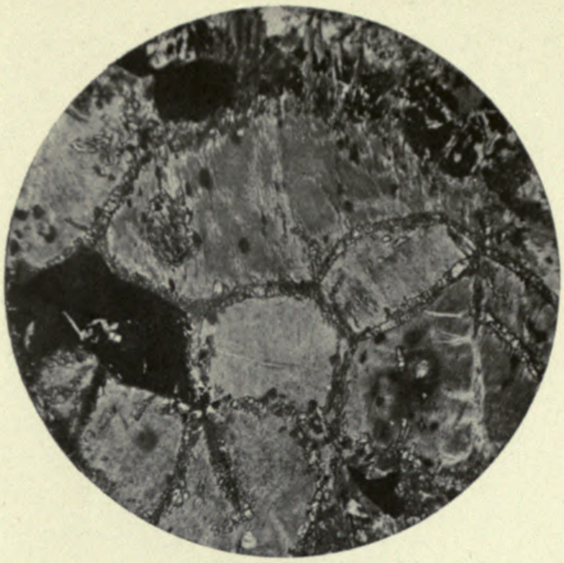
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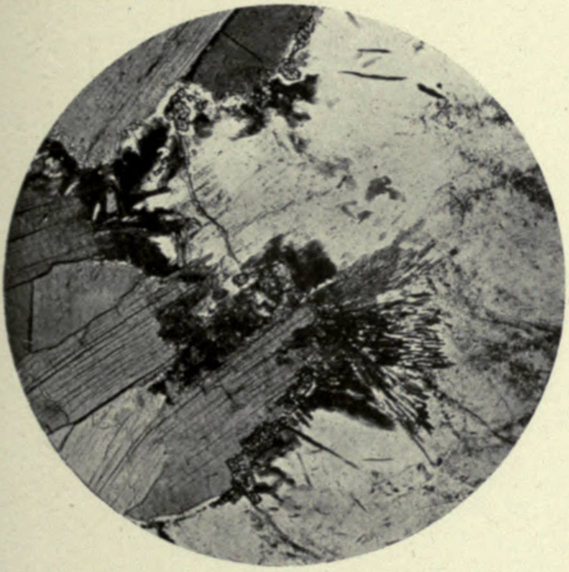
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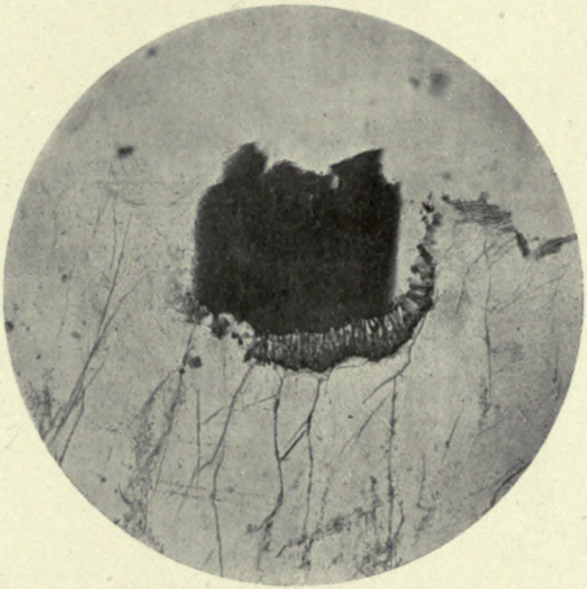
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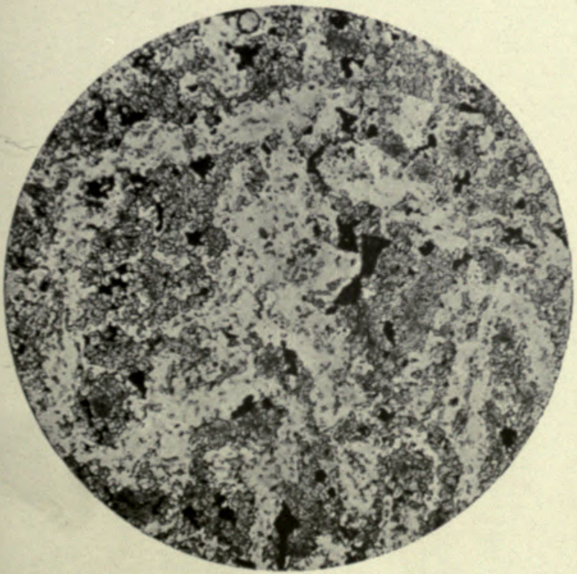
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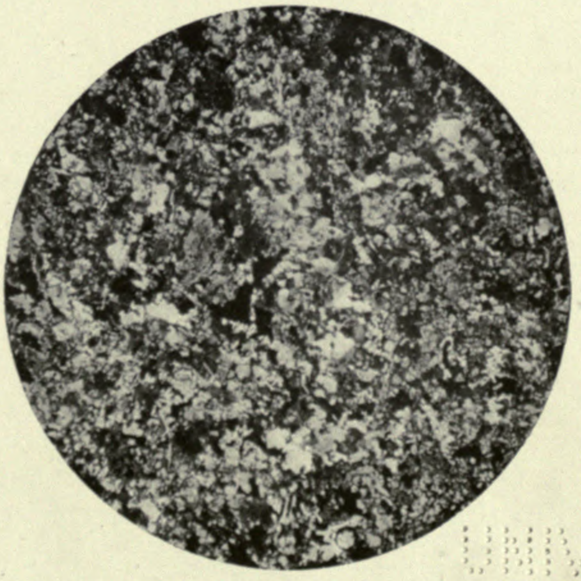
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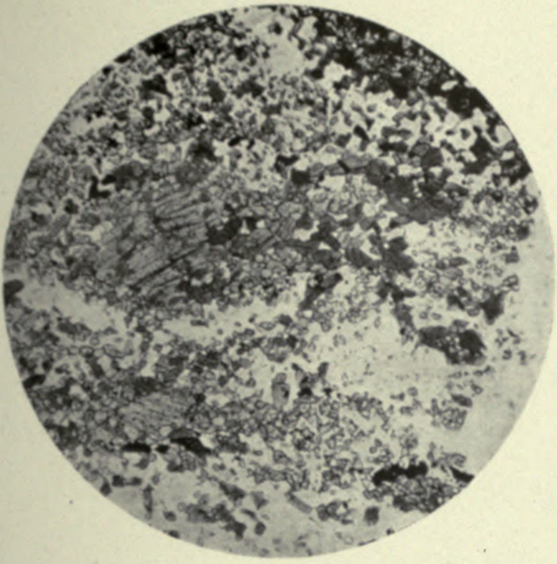

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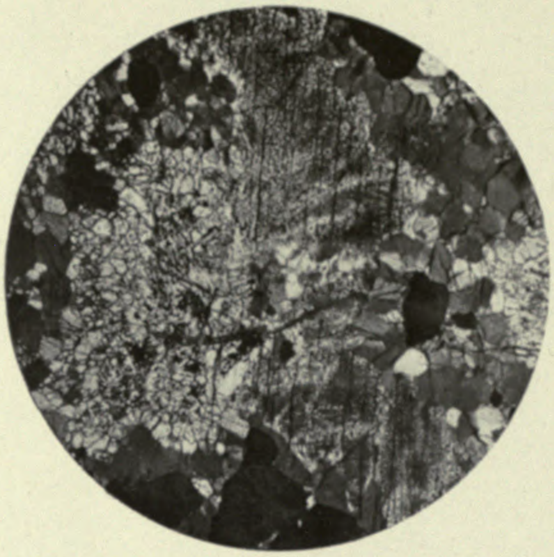

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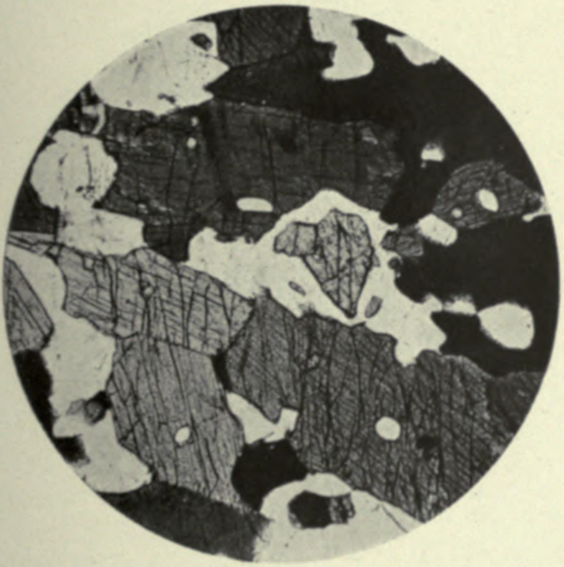

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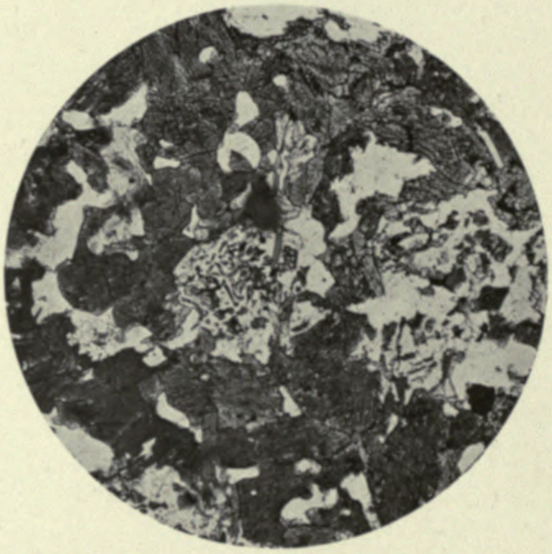

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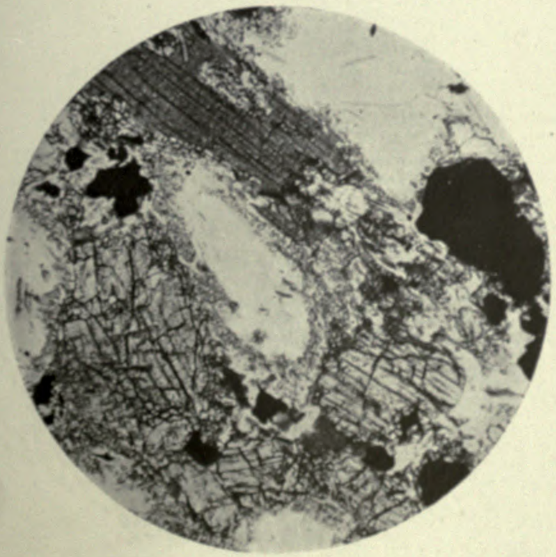

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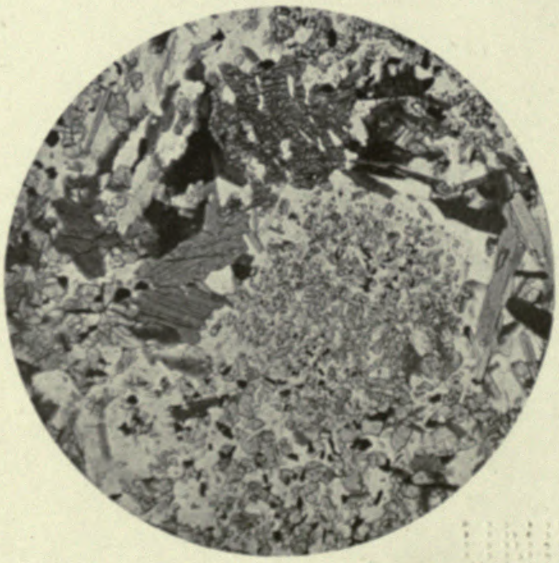

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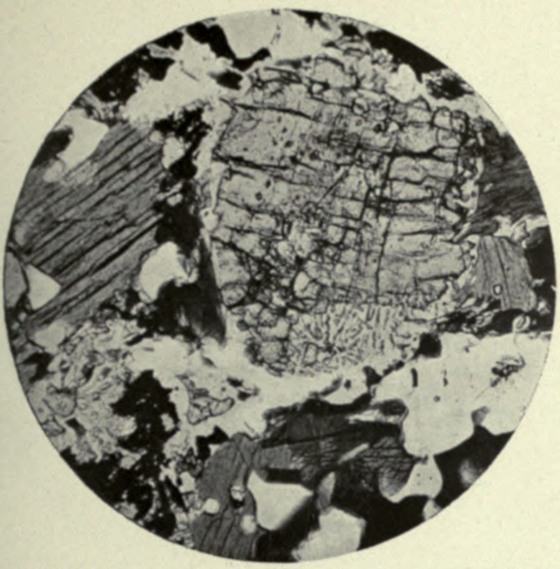

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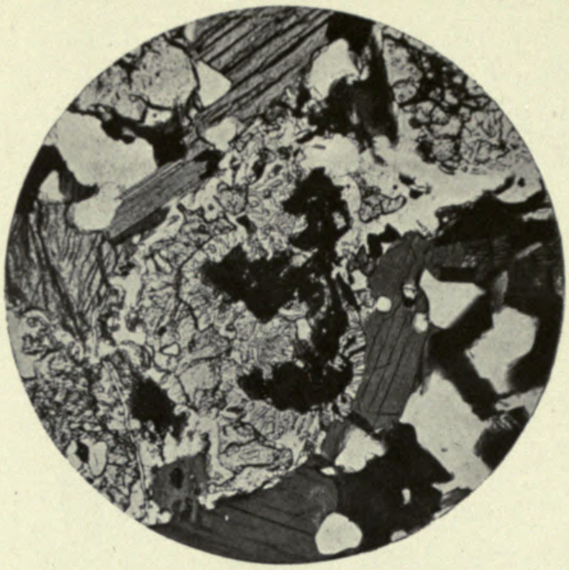

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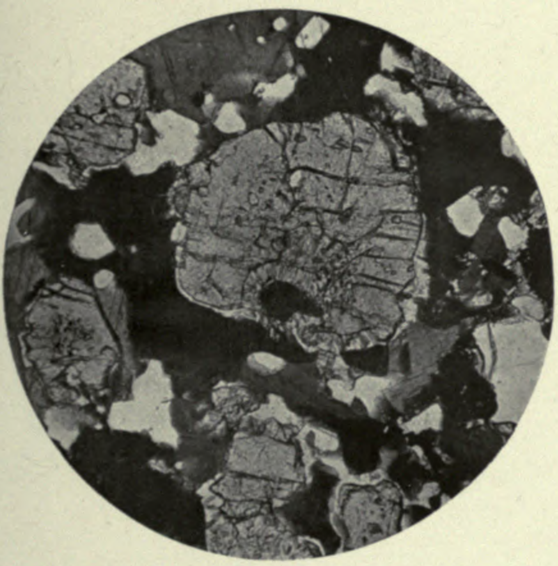

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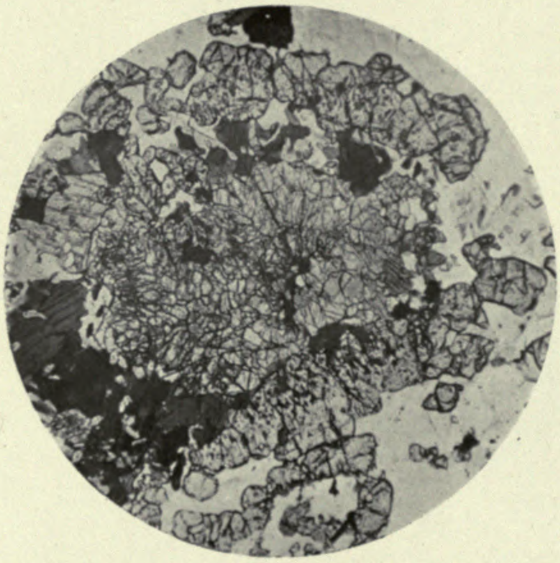

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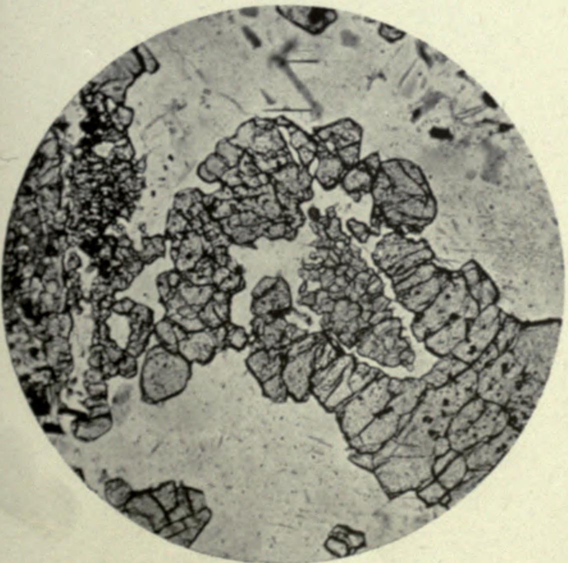

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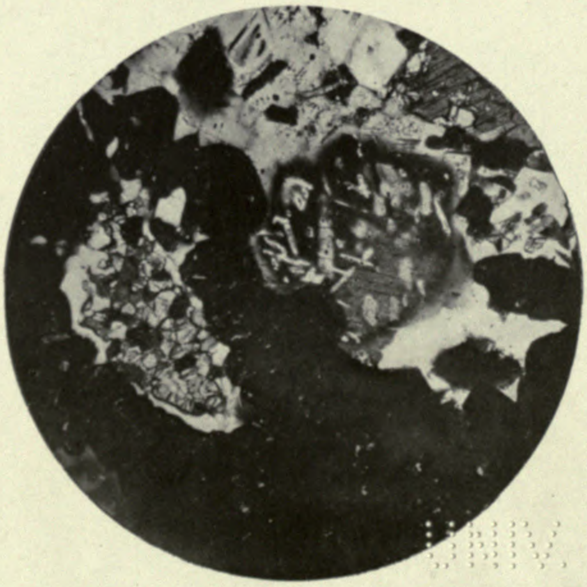

Fig. 6. *Stillwell.*

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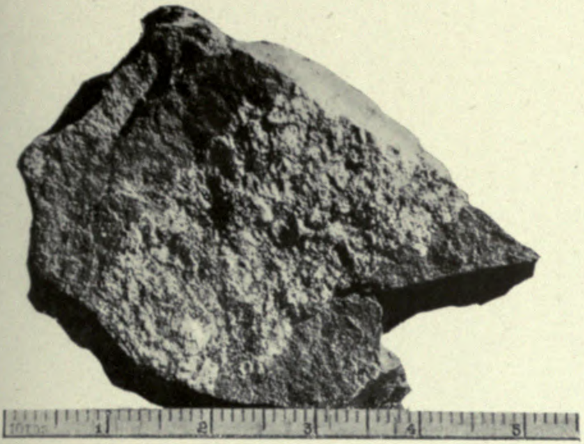

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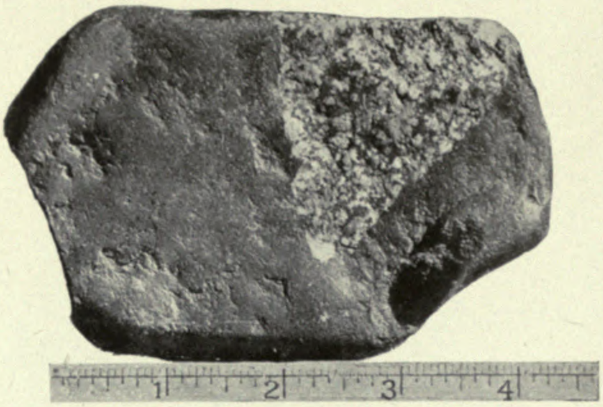

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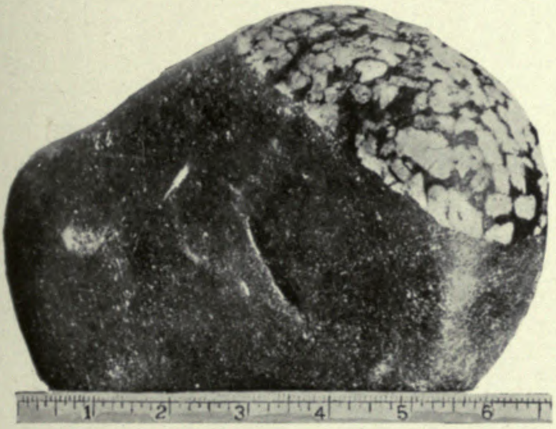

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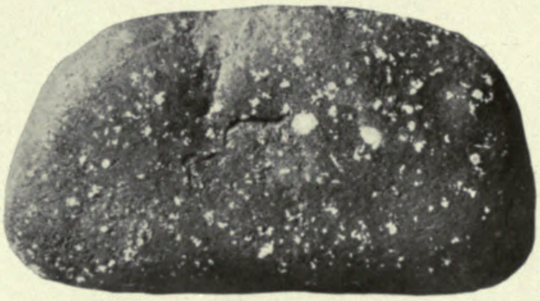

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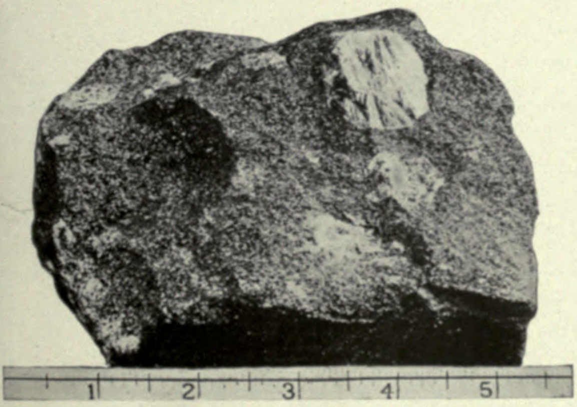

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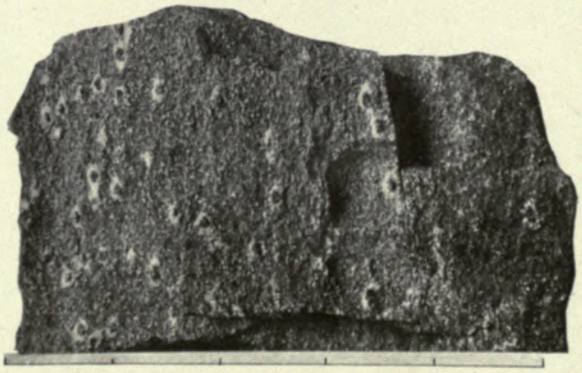

Fig. 6. *Stillwell.*

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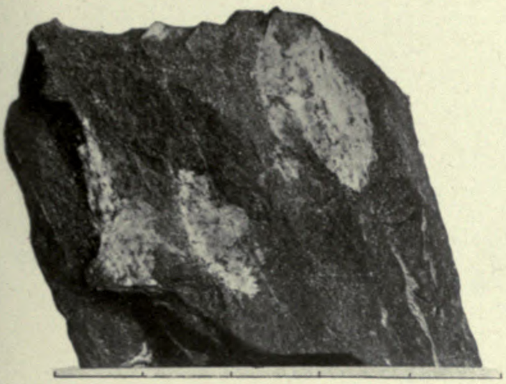


Fig. 1. Stillwell.

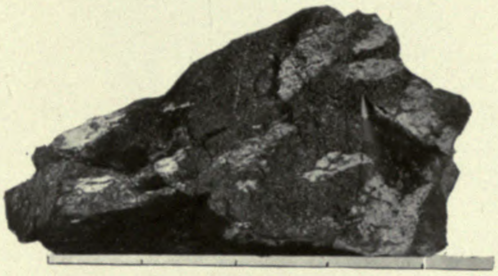
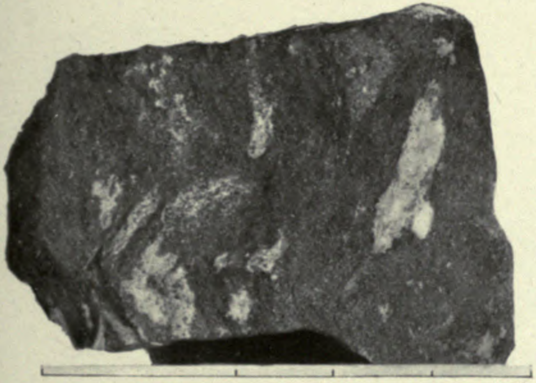


Fig. 2. Stillwell.



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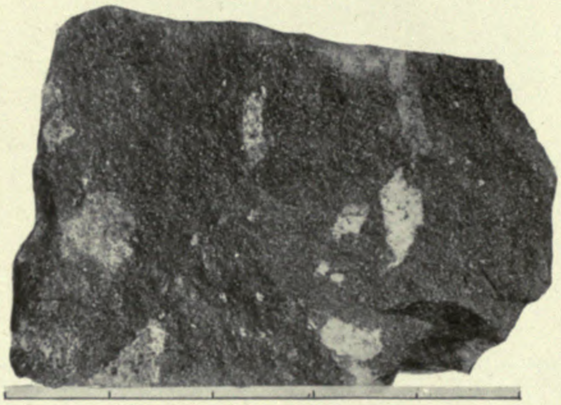

Fig. 4. Stillwell.

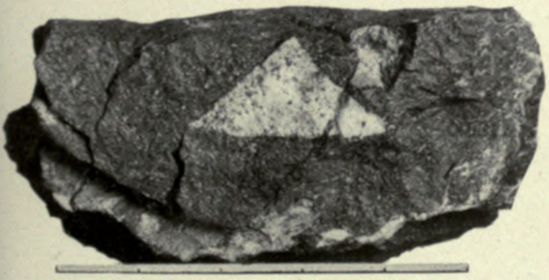

Fig. 5. Stillwell.

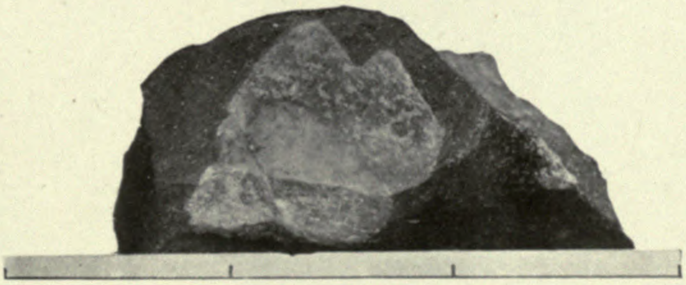

Fig. 6. Stillwell.

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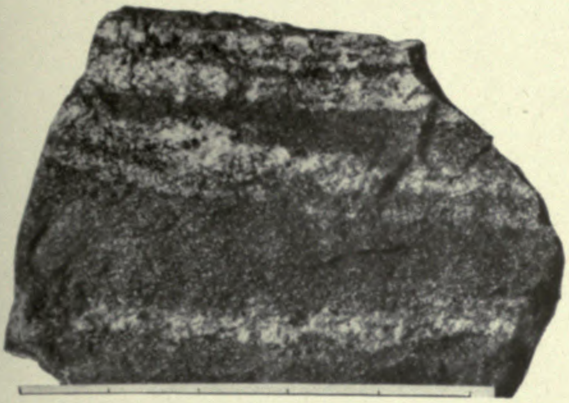

Fig. 1. *Stillwell.*

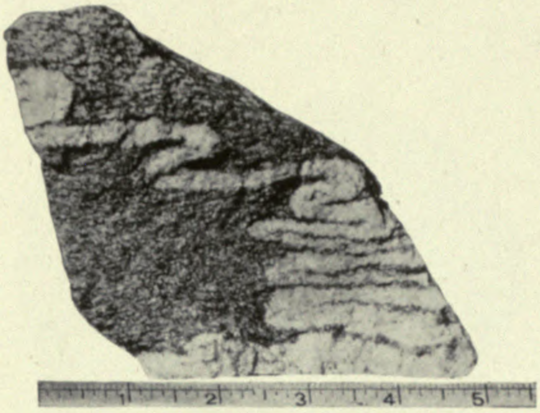

Fig. 2. *Stillwell.*

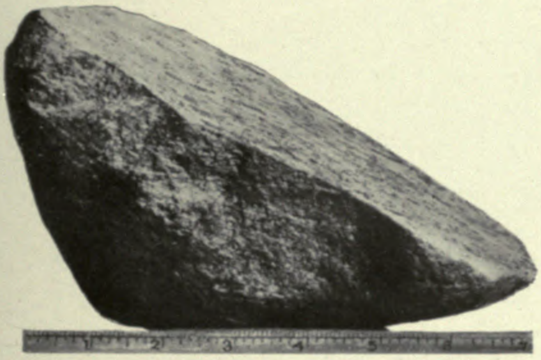

Fig. 3. *Stillwell.*

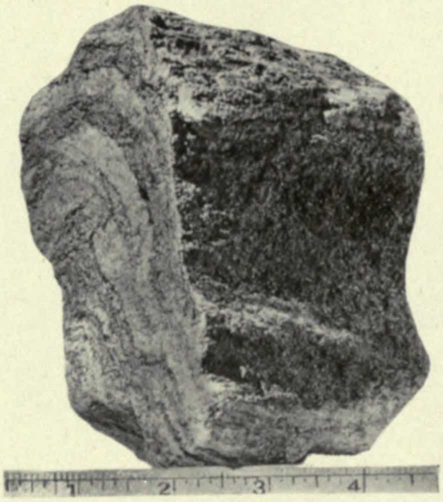

Fig. 4. *Stillwell.*

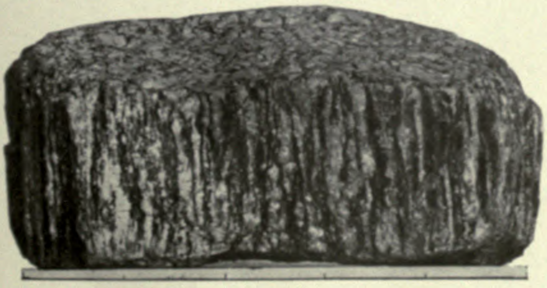

Fig. 5. *Stillwell.*

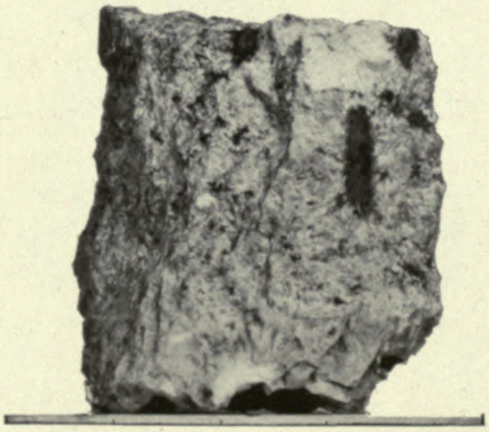

Fig. 6. *Stillwell.*

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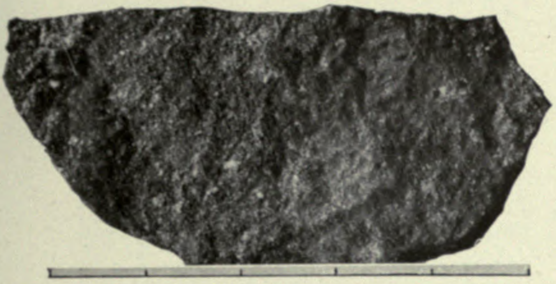

Fig. 1. Stillwell.

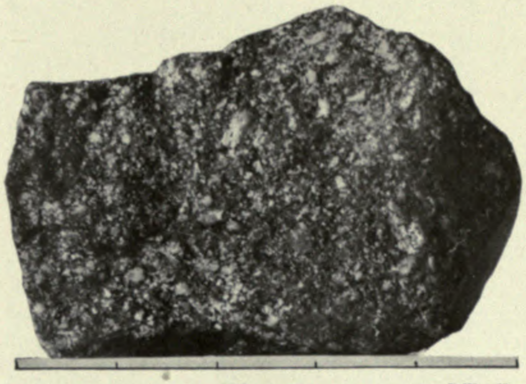

Fig. 2. Stillwell.

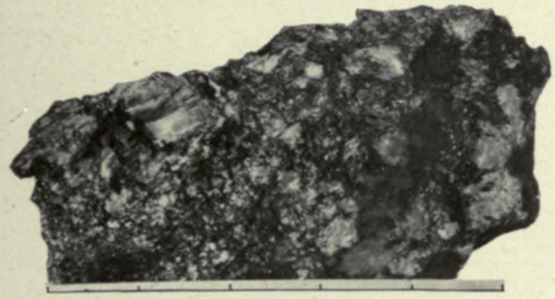

Fig. 3. Stillwell.

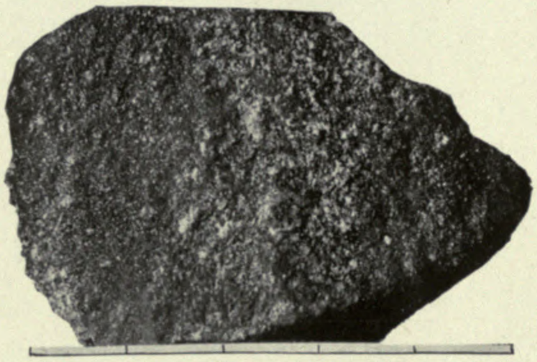

Fig. 4. Stillwell.

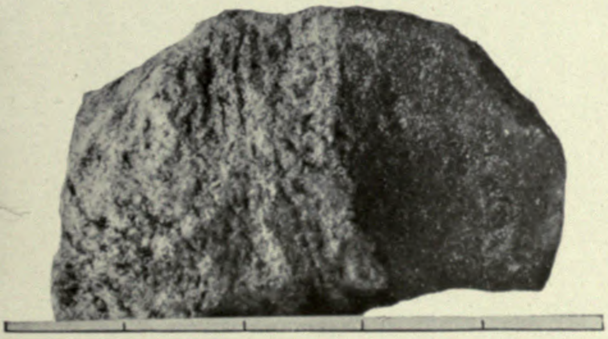

Fig. 5. Stillwell.

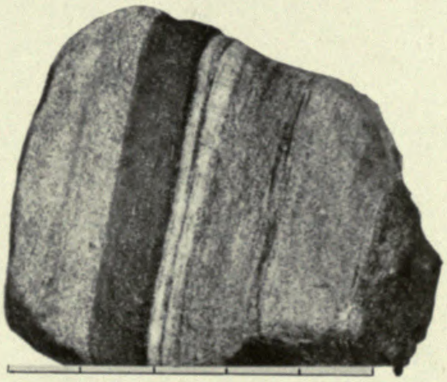

Fig. 6. Stillwell.

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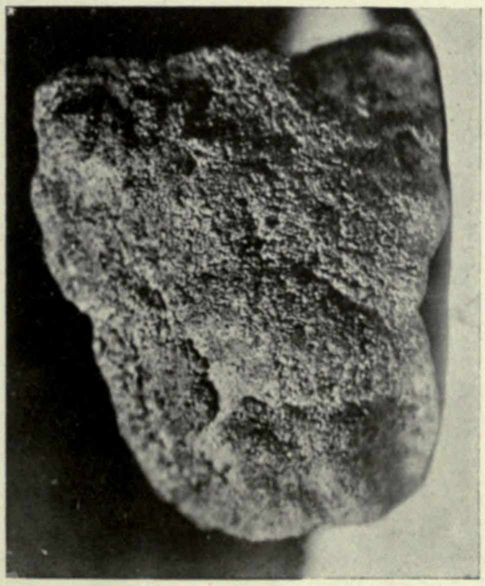

Fig. 1.

F. Chapman.

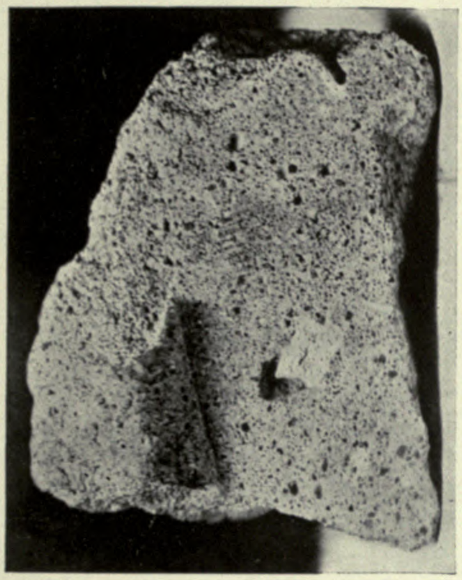

Fig. 2.

F. Chapman.

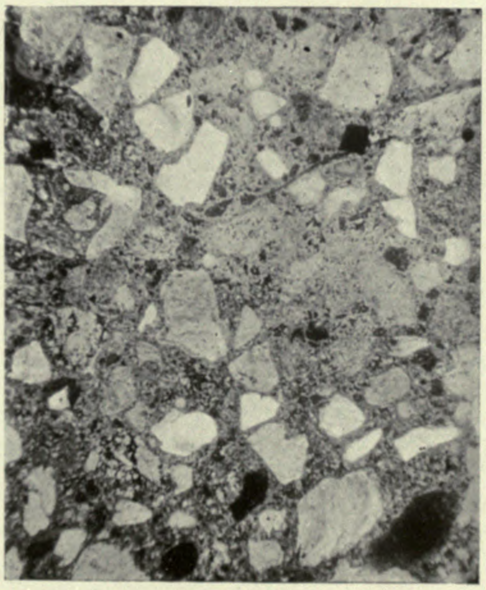

Fig. 3.

F. Chapman.

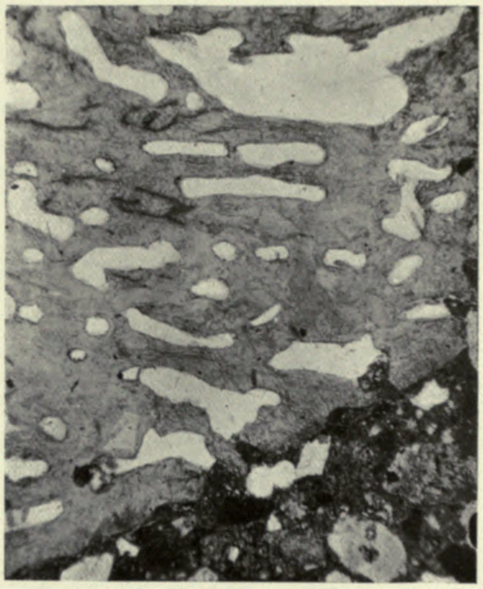

Fig. 4.

F. Chapman.

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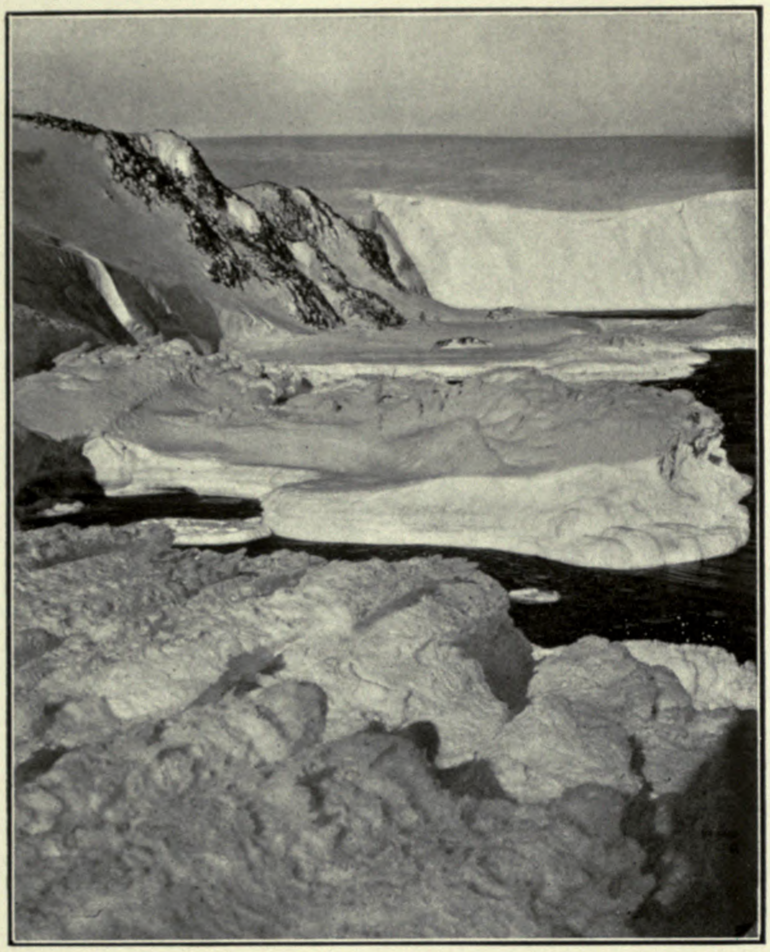

Fig. 1. *Hurley.*

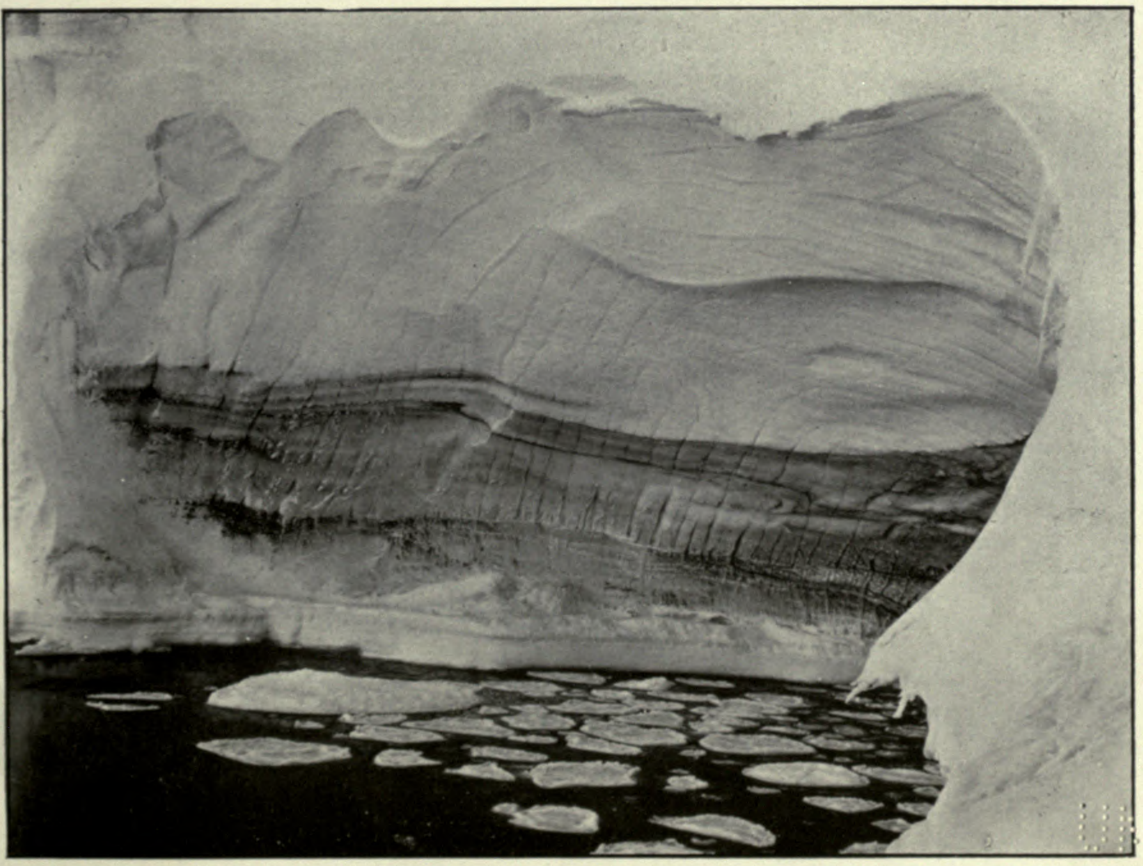

Fig. 2. *Hurley.*

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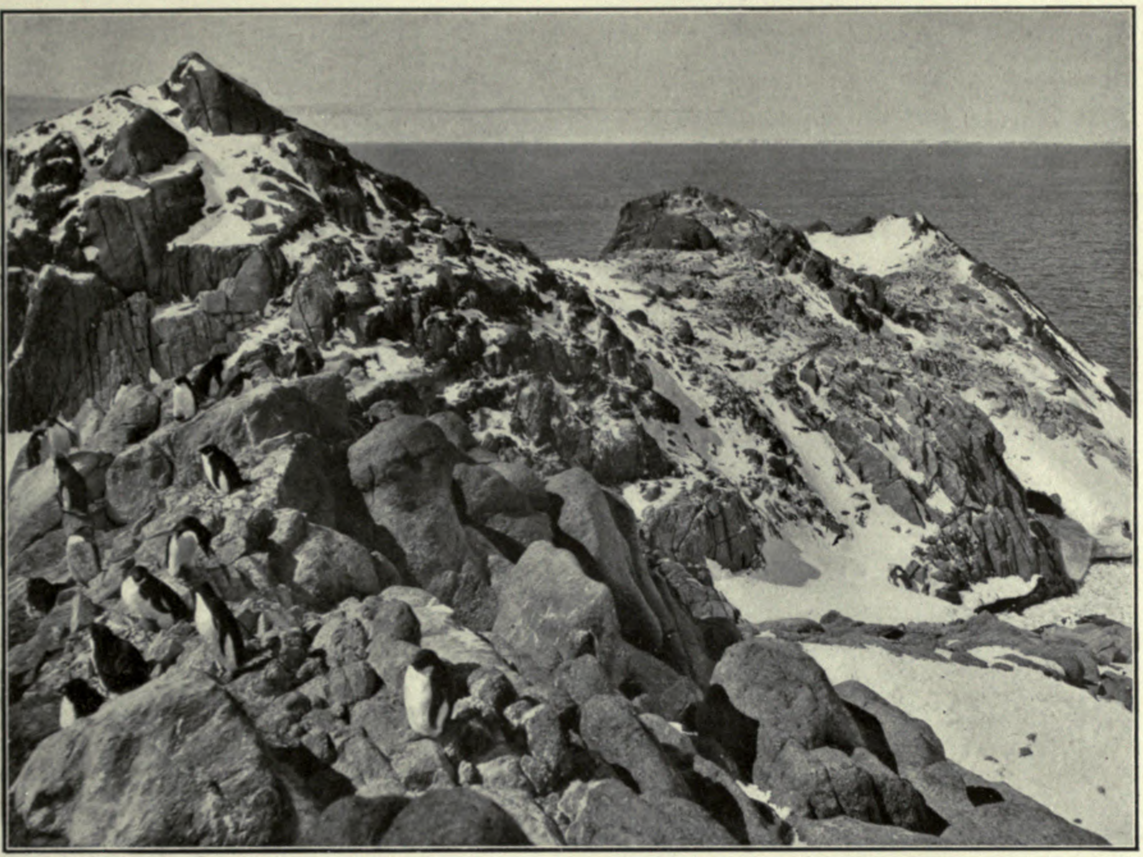

Fig. 1. *Hurley.*

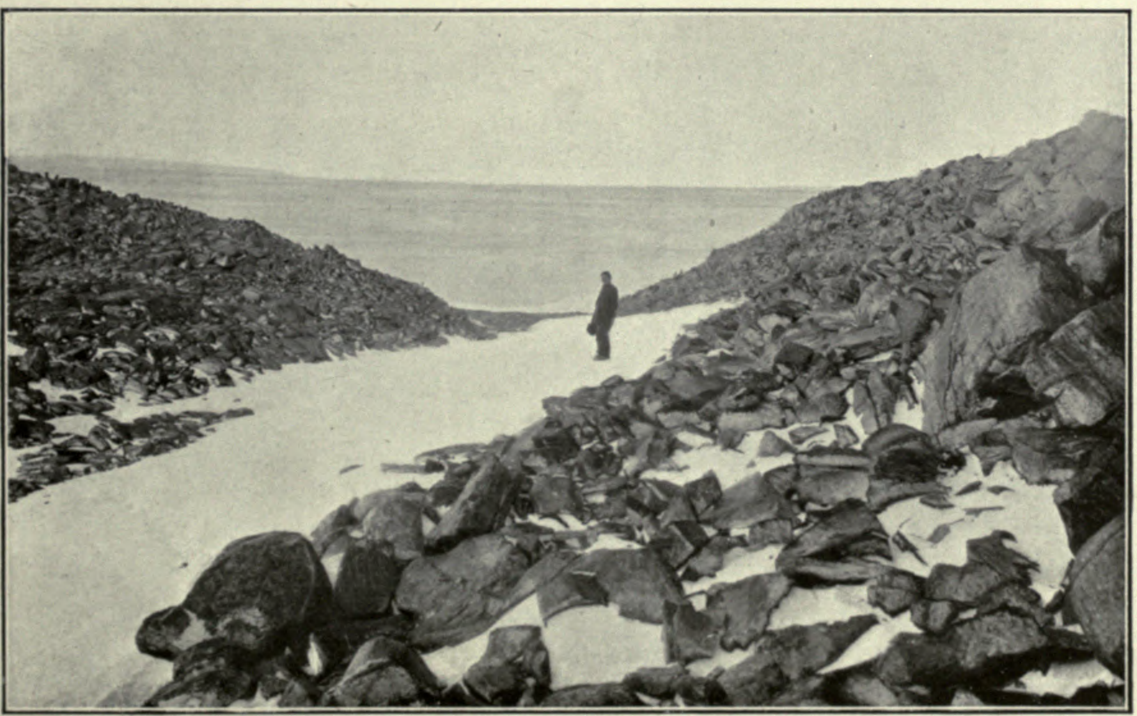

Fig. 2. *Hurley.*

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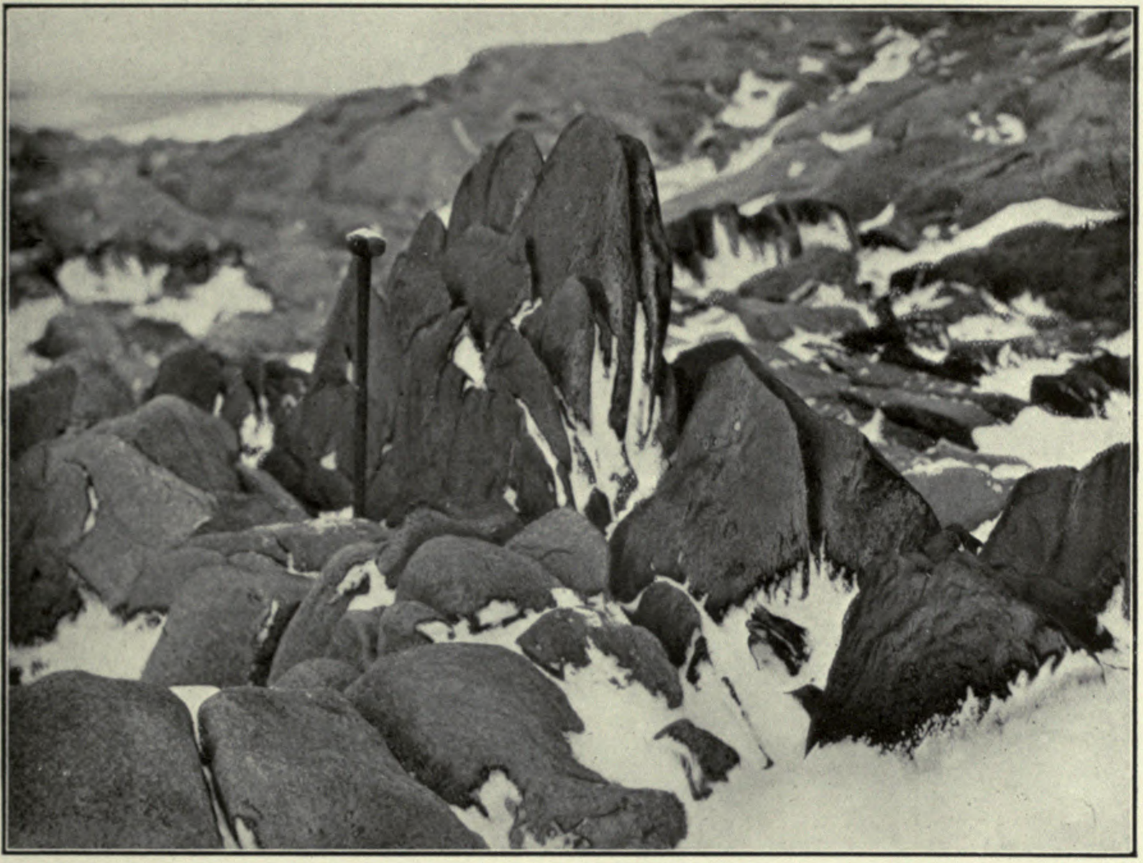

Fig. 1. *Hurley.*

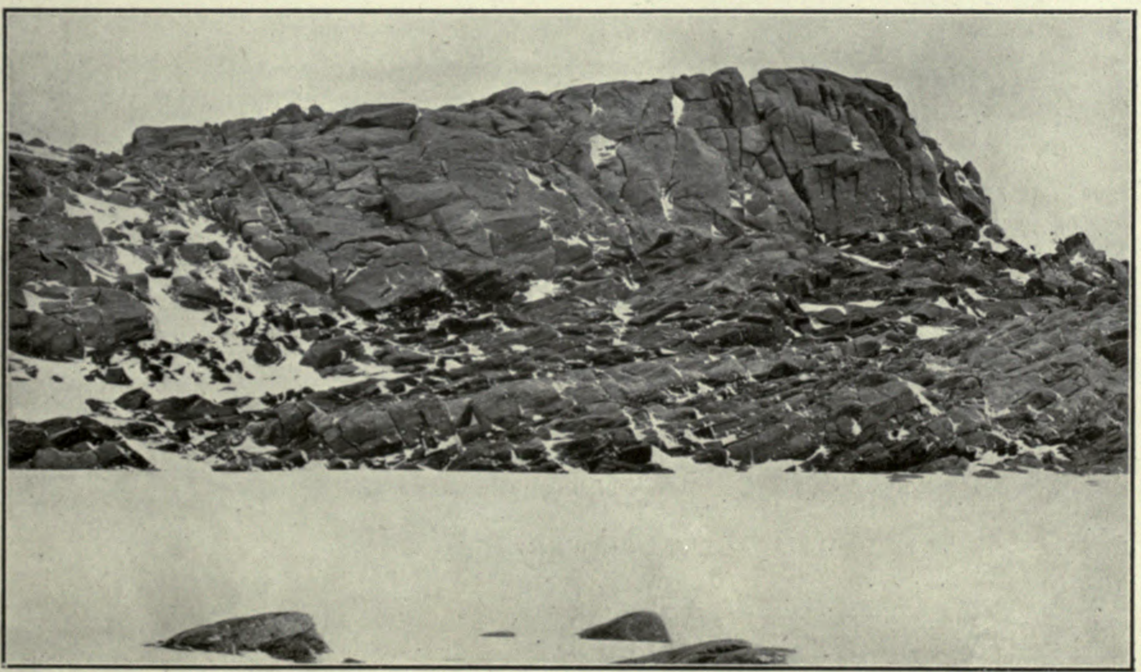

Fig. 2. *Hurley.*

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PLATE XVII.

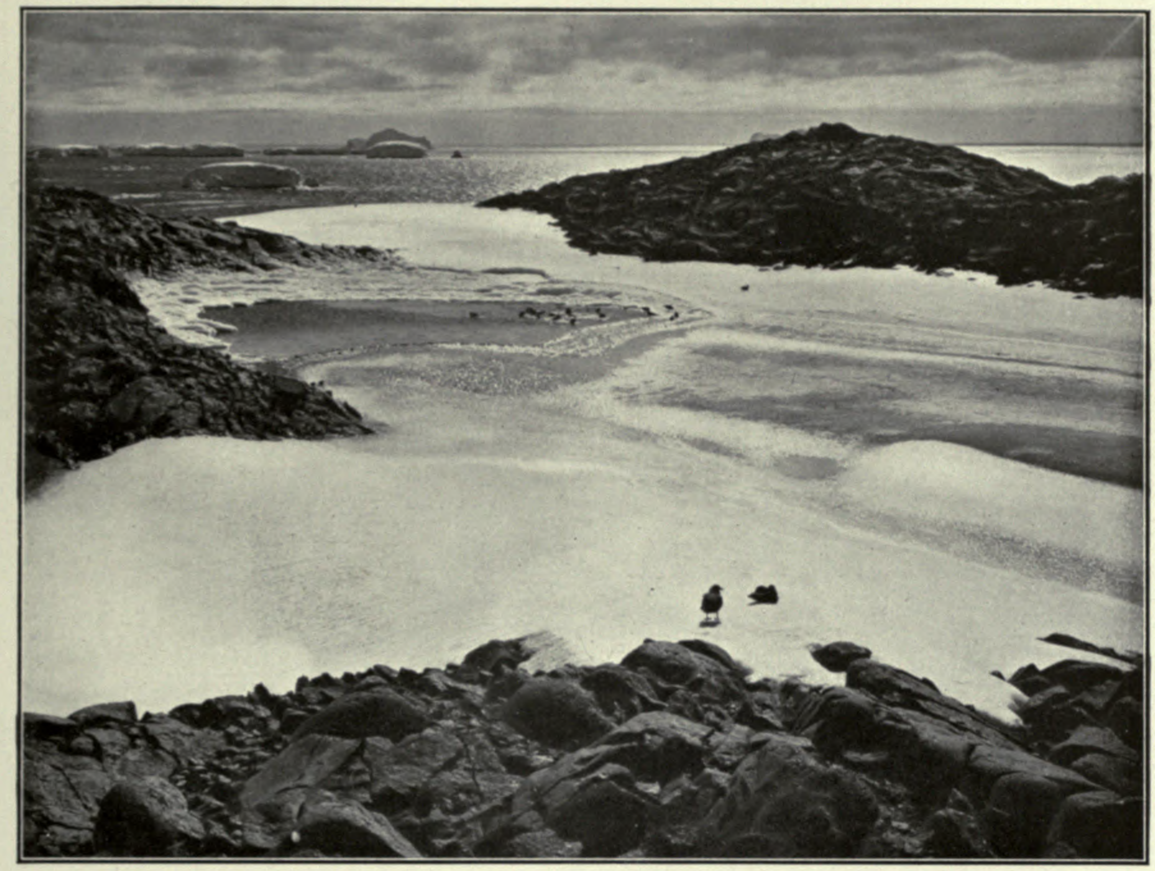

Fig. 1.

Hurley.

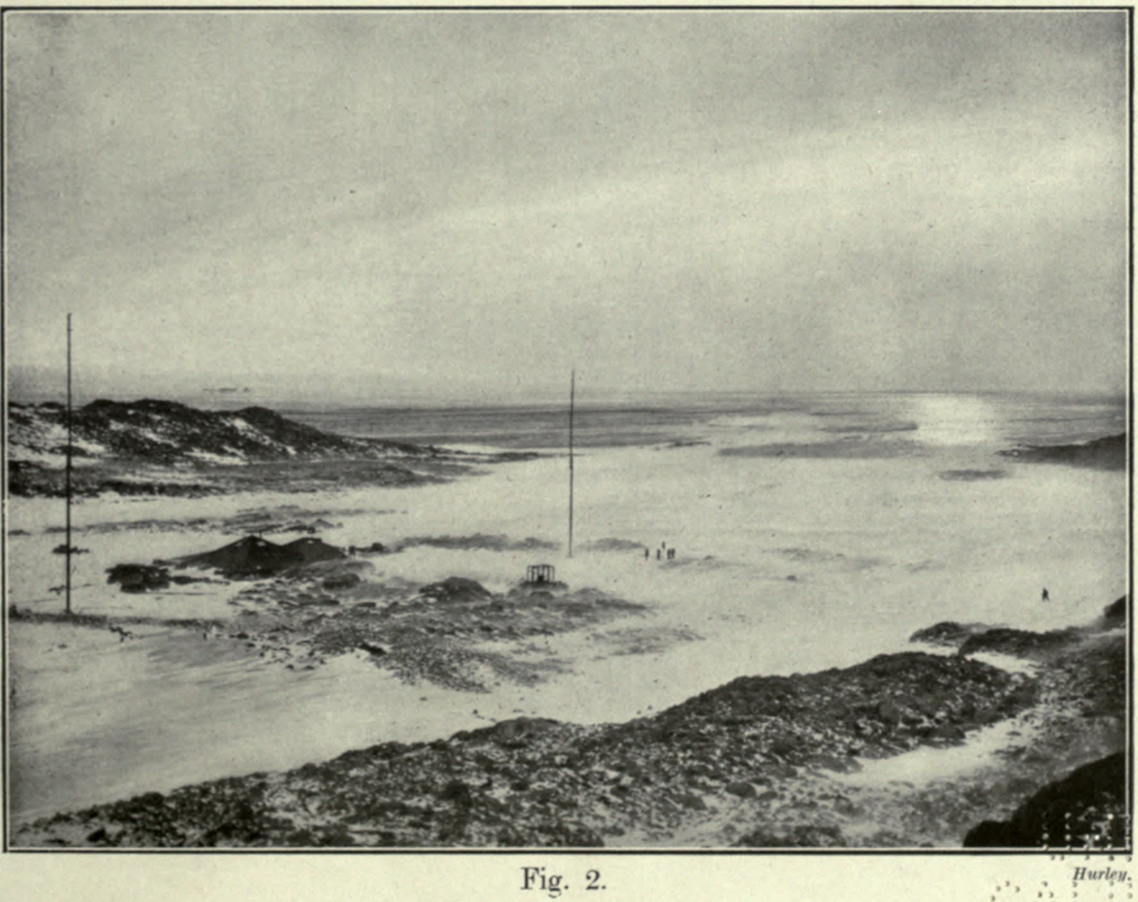

Fig. 2.

Hurley.

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10 VIII
[illegible]

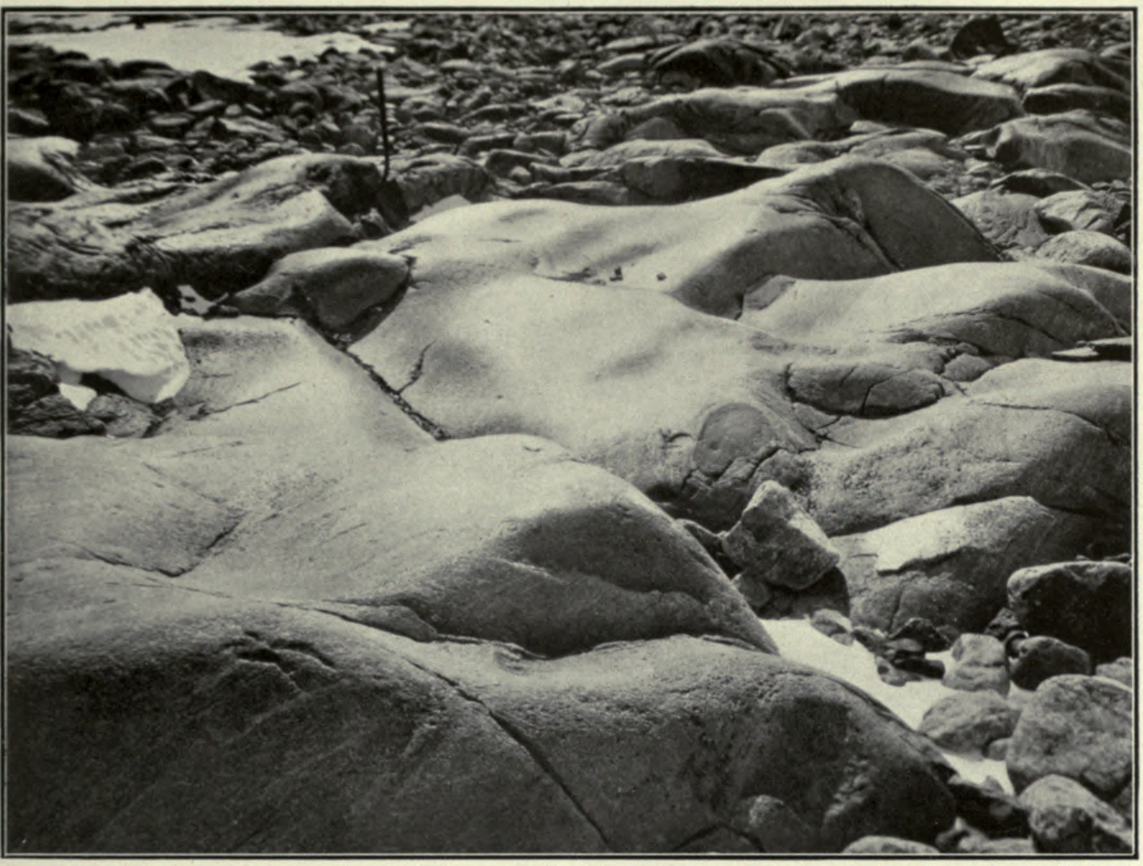

Fig. 1. Hurley.

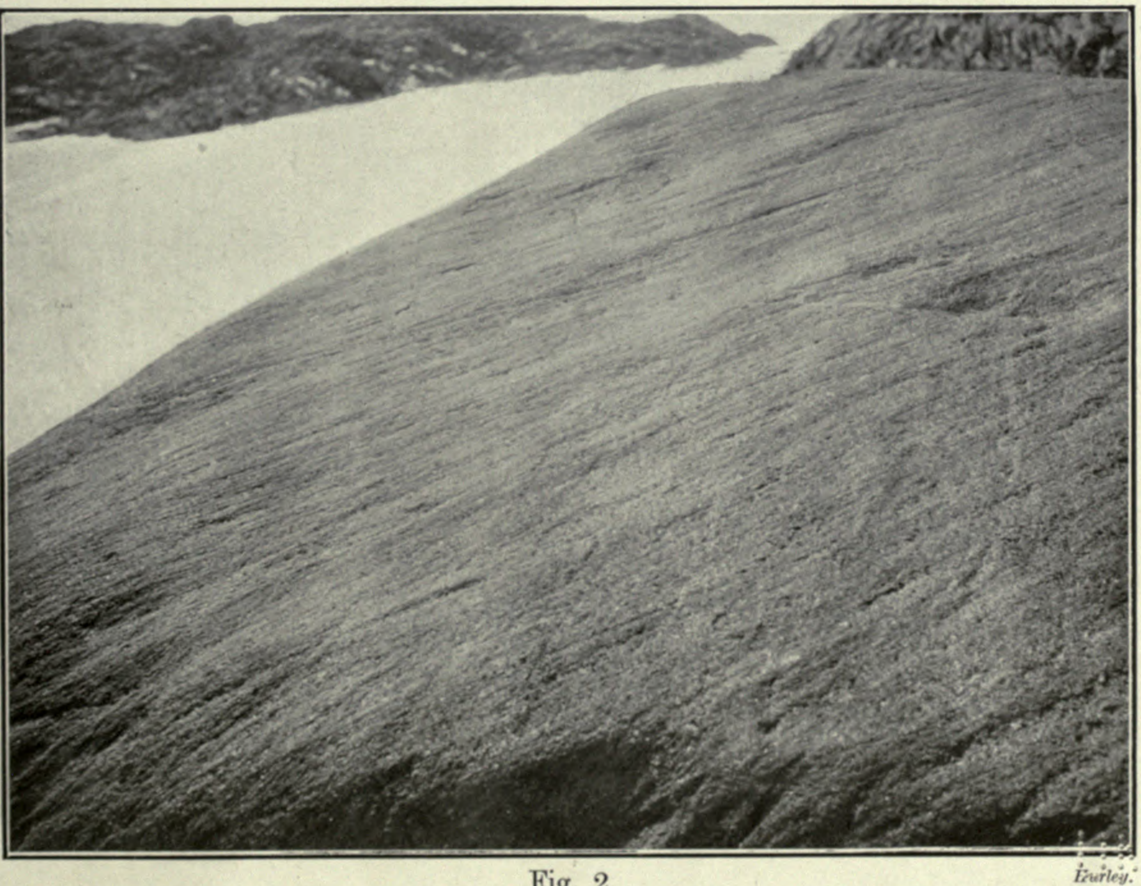

Fig. 2. Hurley.

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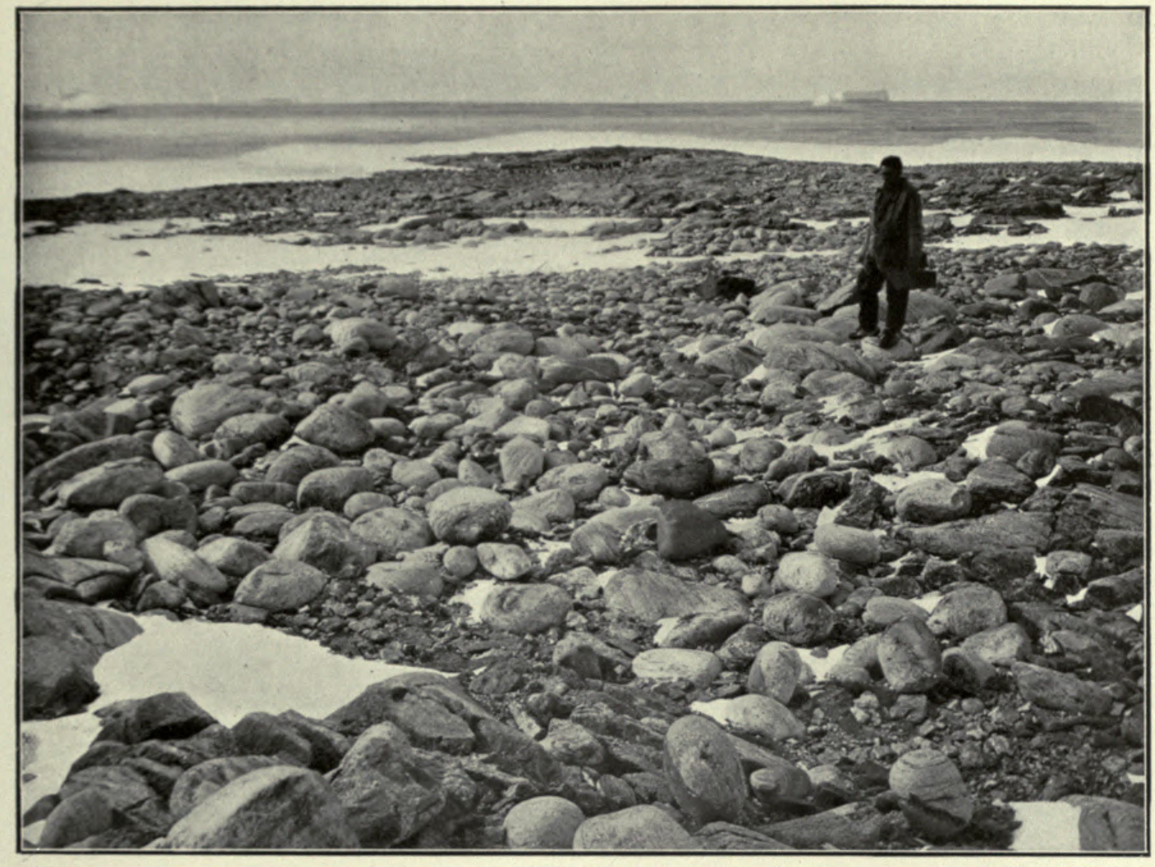

Fig. 1.

Hurley.

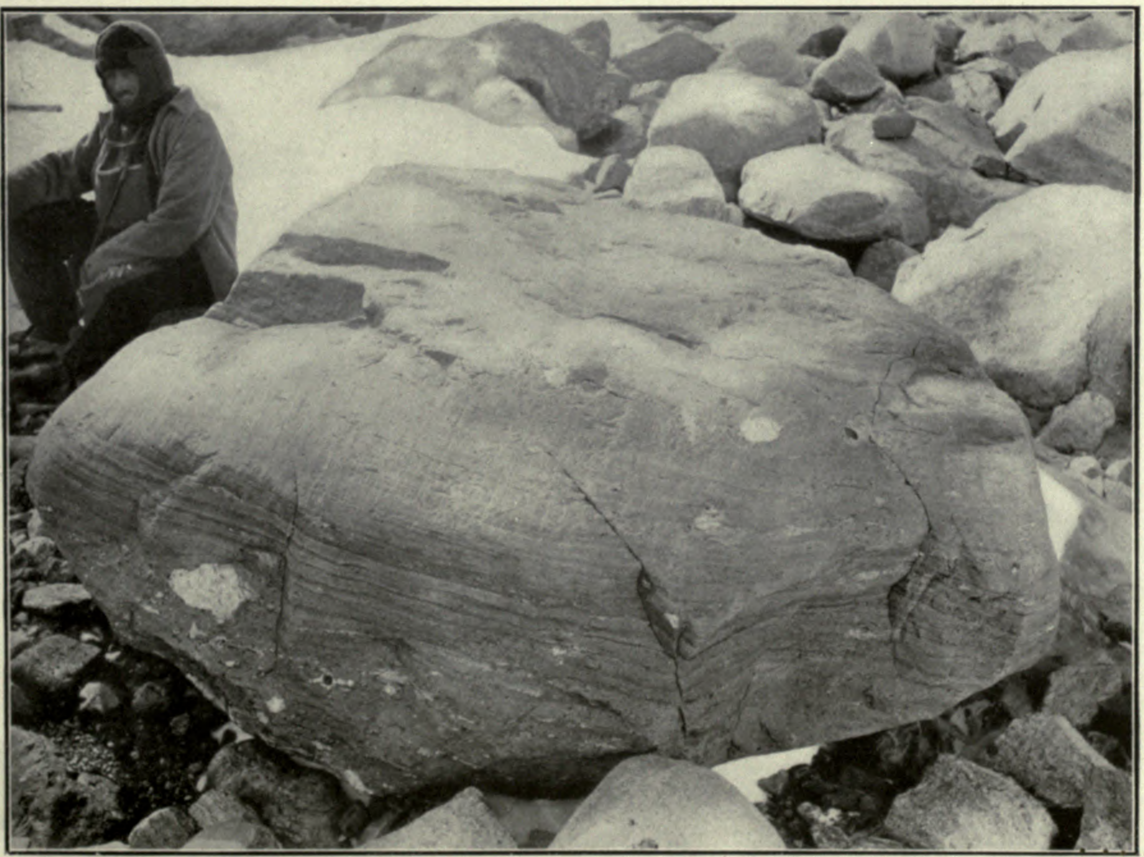

Fig. 2.

Hurley.

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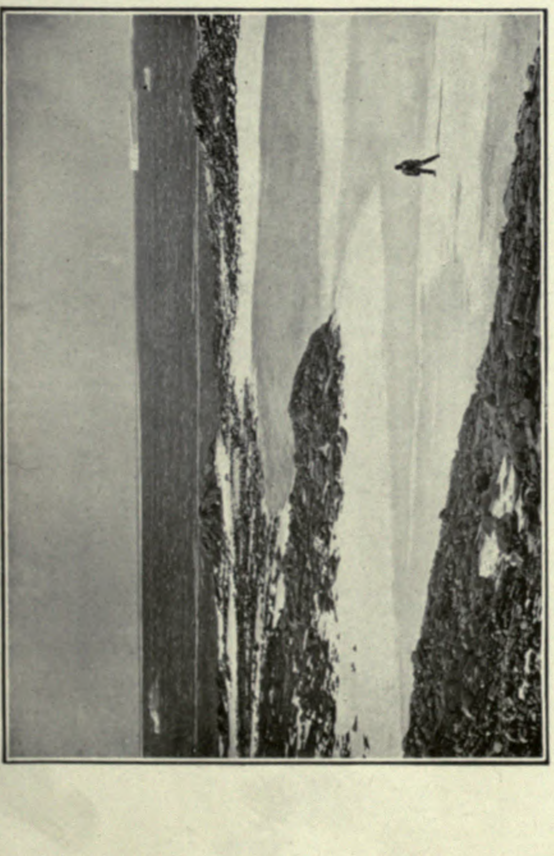
Fig. 1.
Hurley.

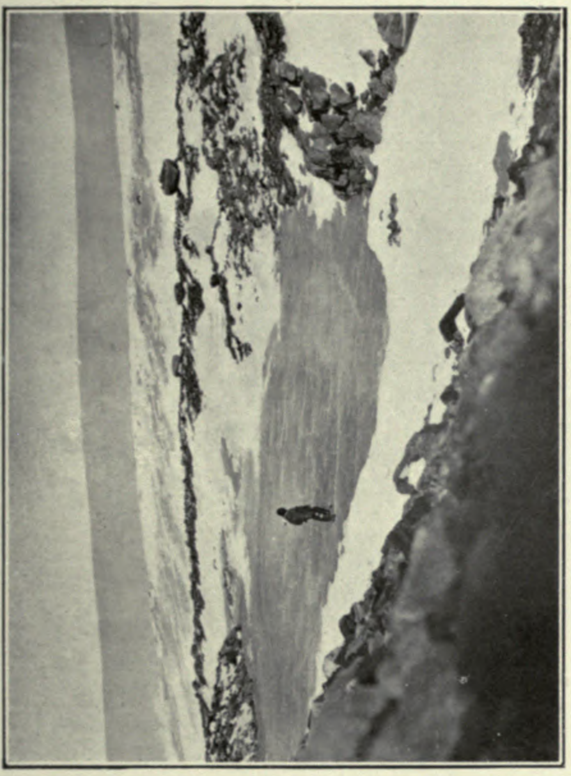
Fig. 2.
Hurley.

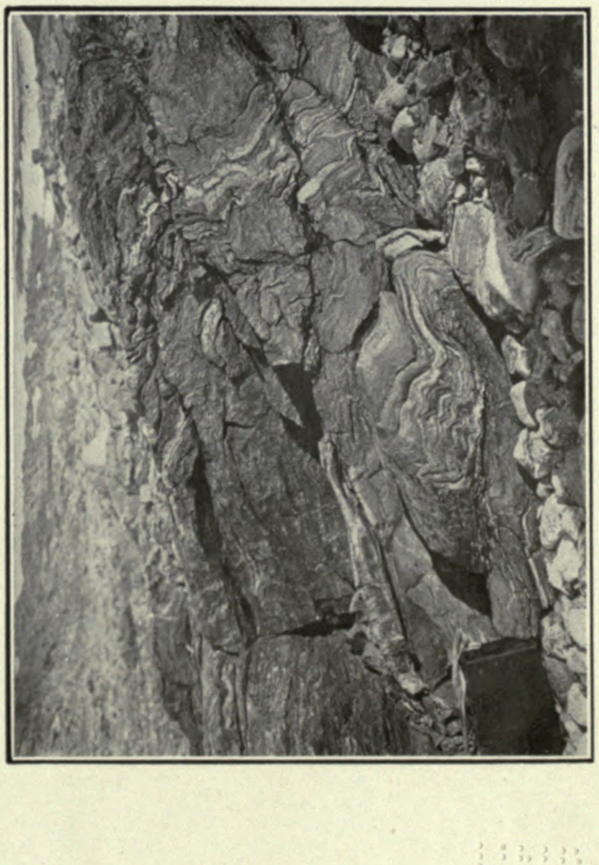
Fig. 3.
Hurley.

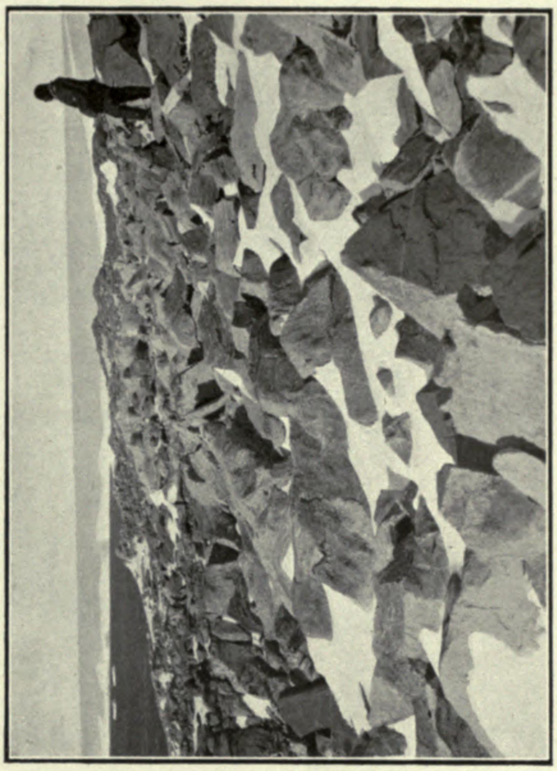
Fig. 4.
Hurley.

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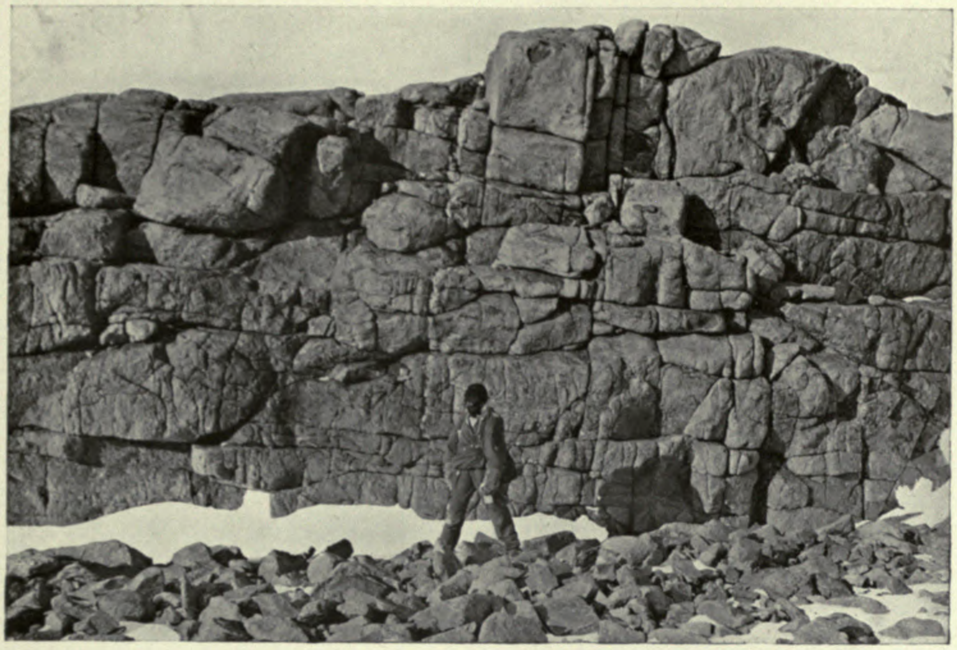

Fig. 1. *Hurley.*

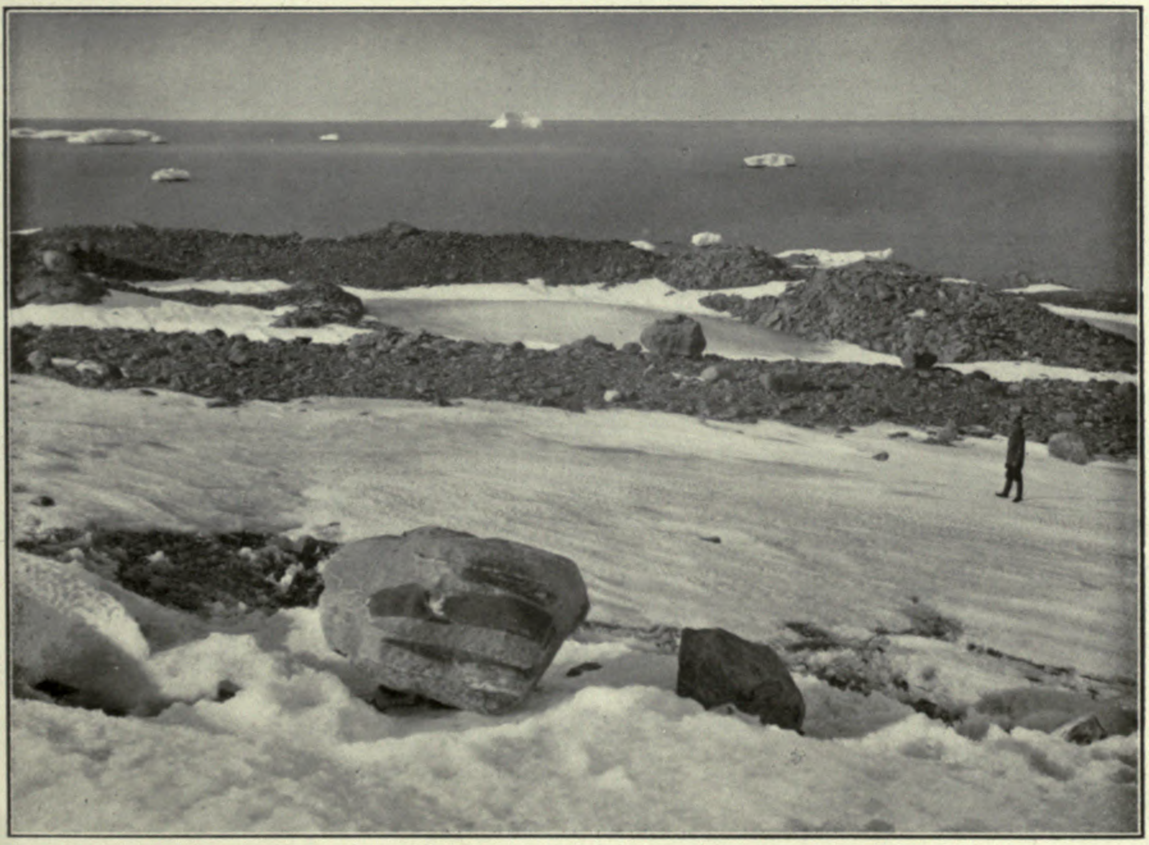

Fig. 2. *Hurley.*

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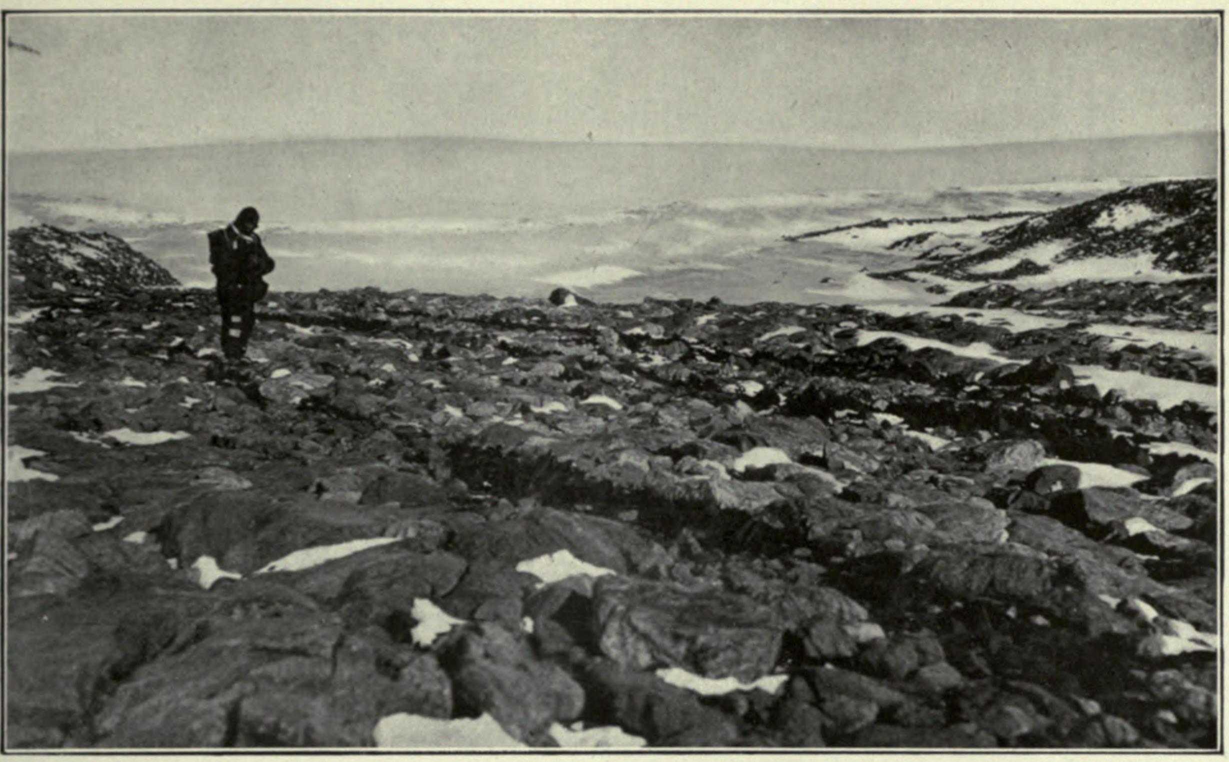

Fig. 1.

Hurley.

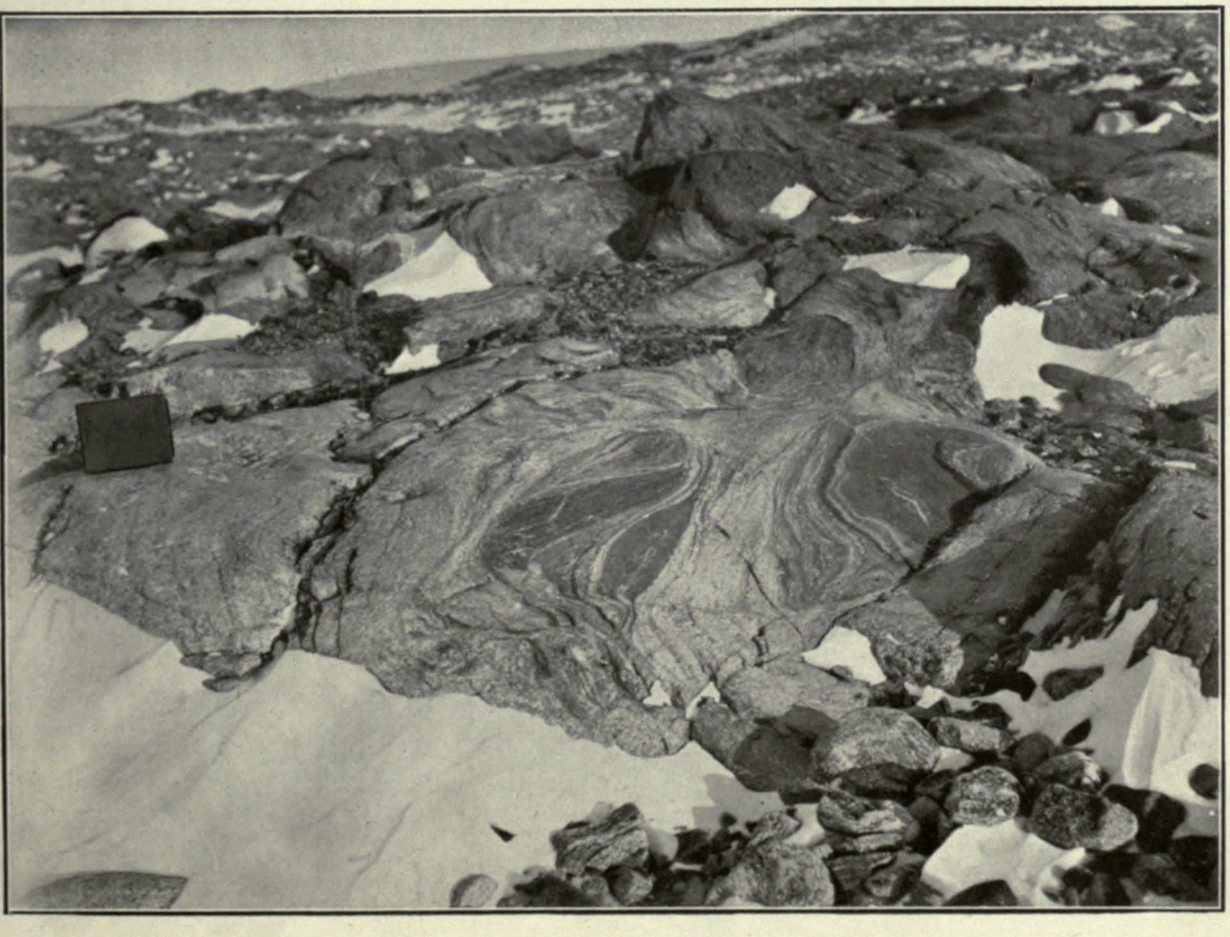

Fig. 2.

Hurley.

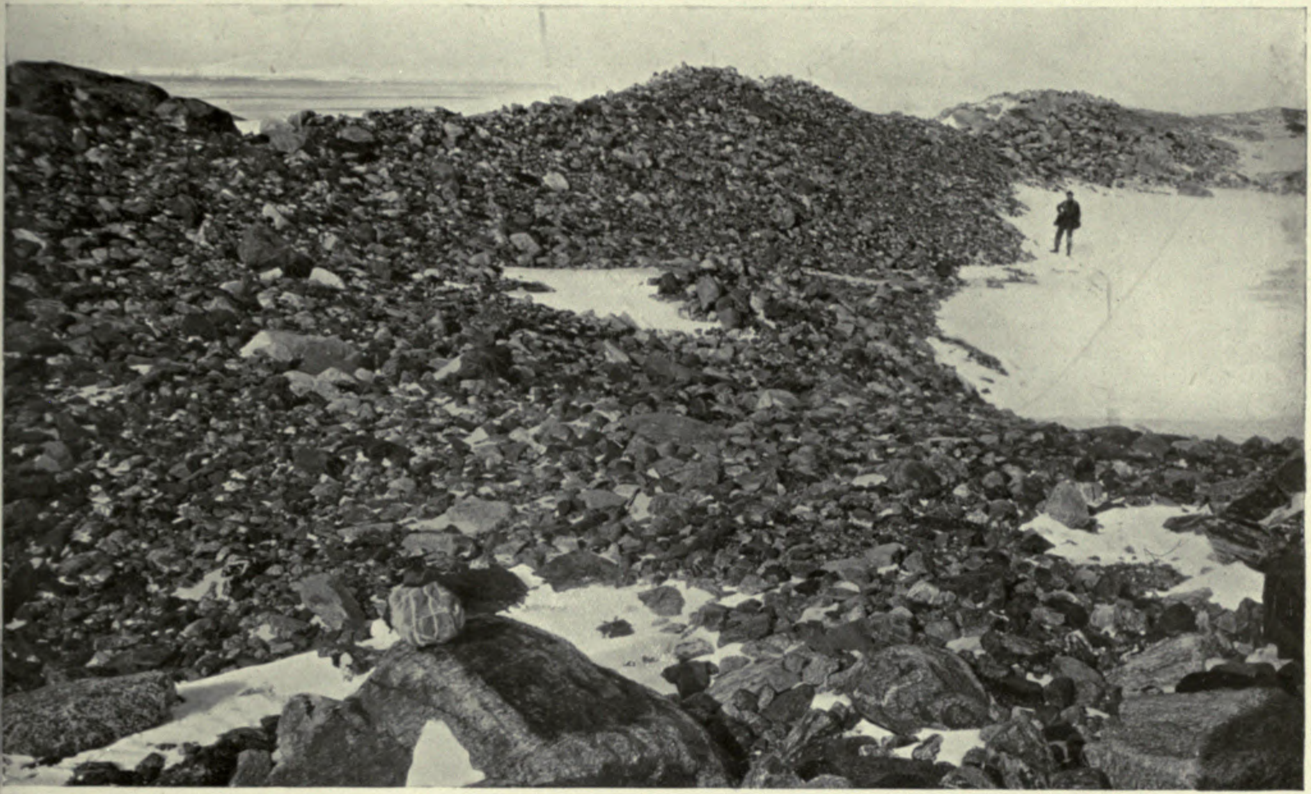

Fig. 1.

Hurley.

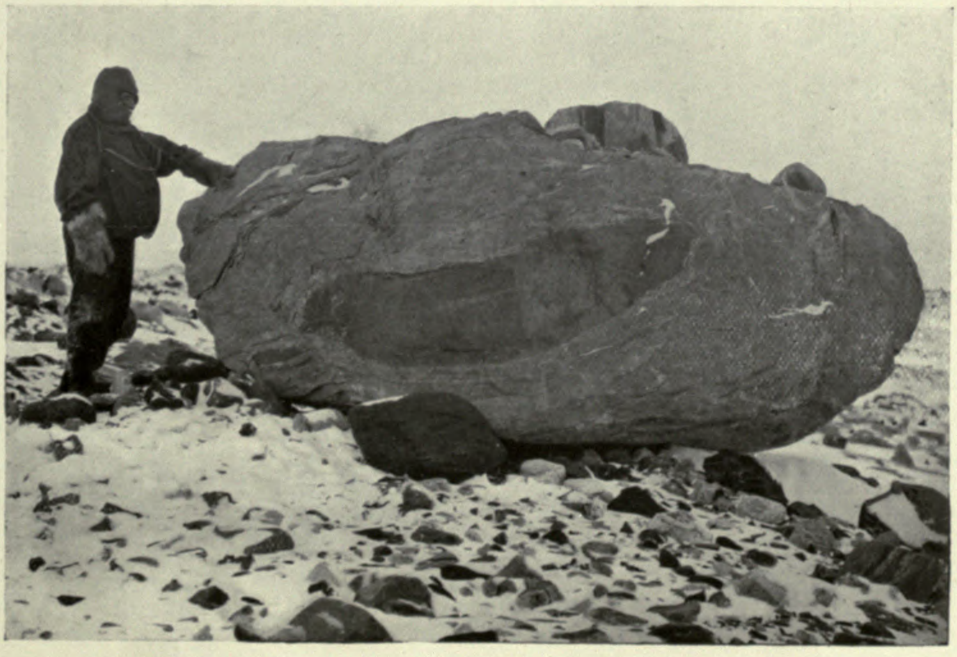

Fig. 2.

Hurley.

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PLATE XXIV.

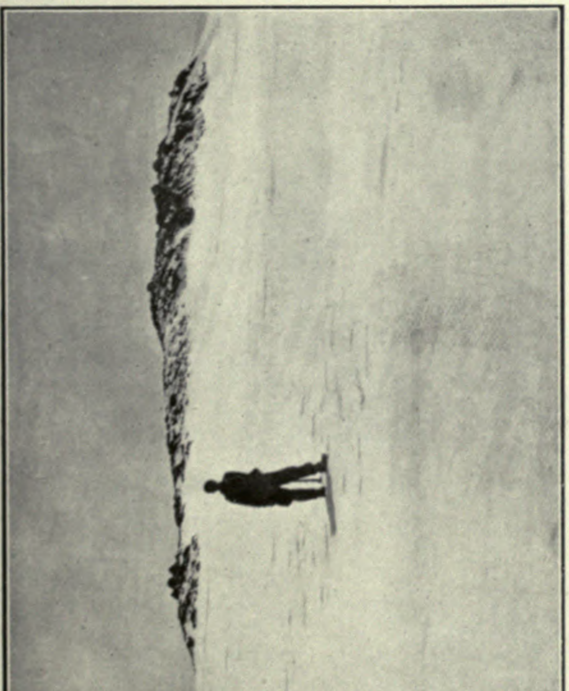


Fig. 1.

Laseron.

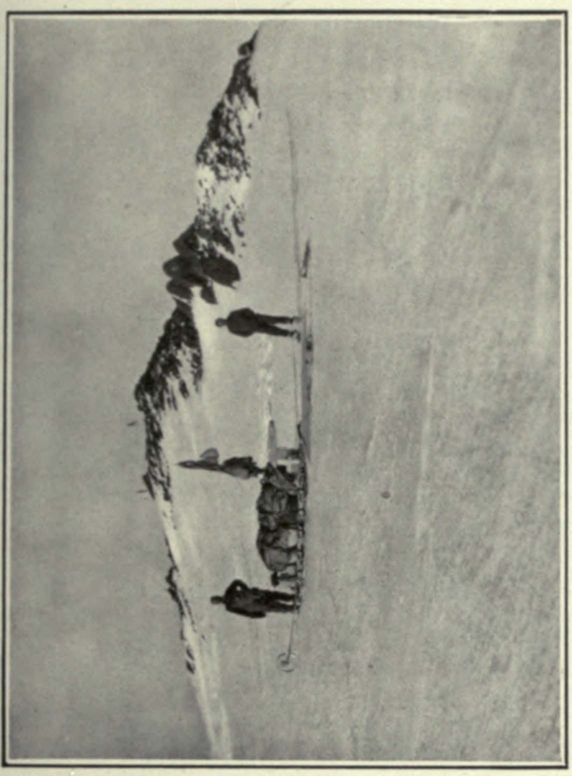


Fig. 2.

Laseron.

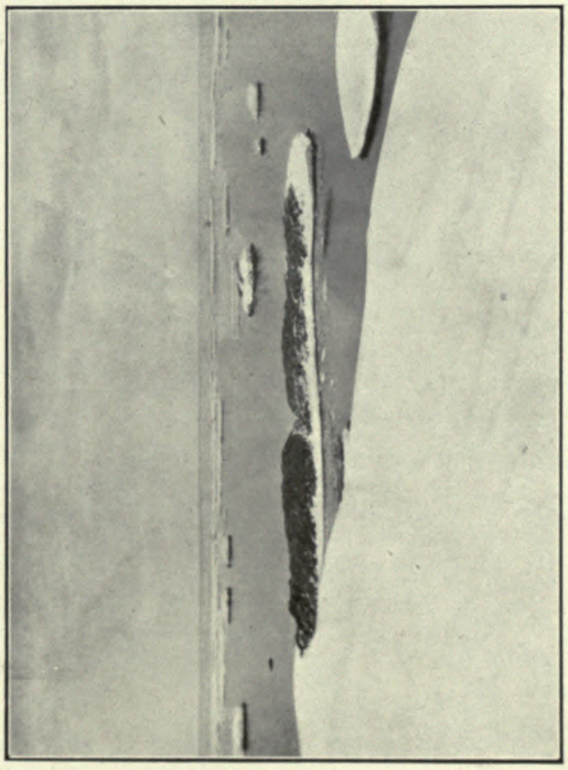


Fig. 3.

Laseron.

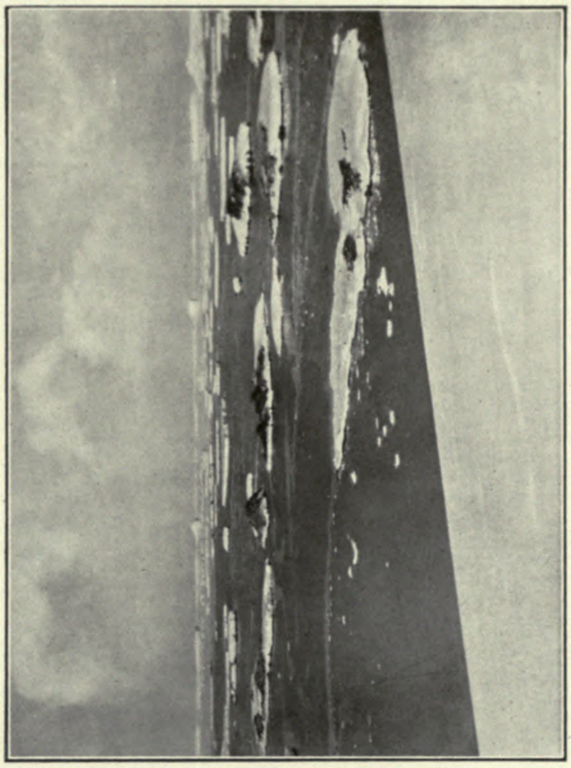
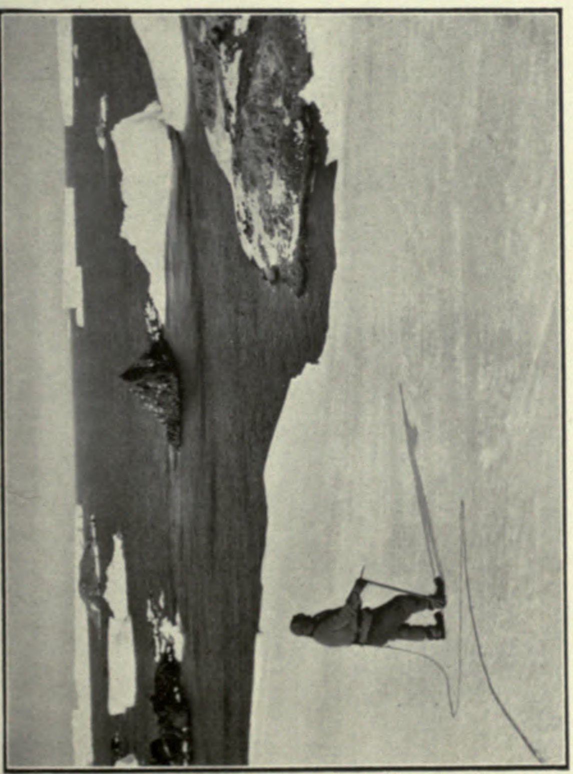


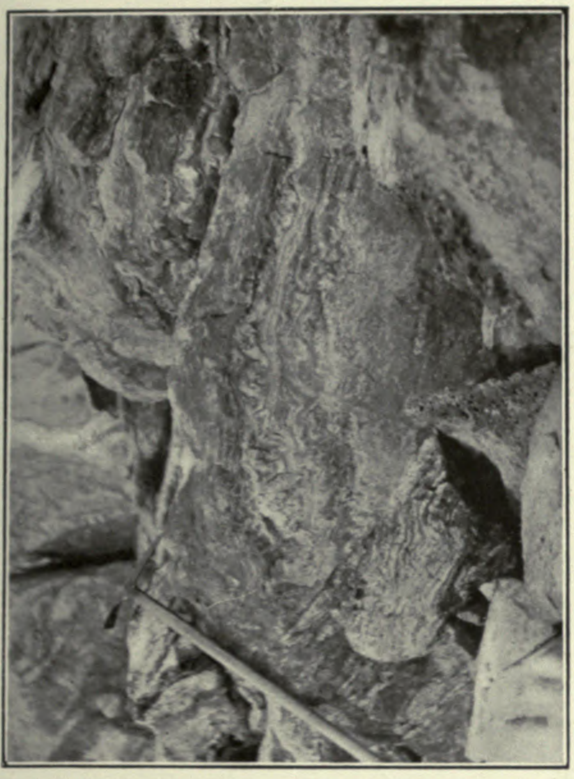
Fig. 4.

Laseron.



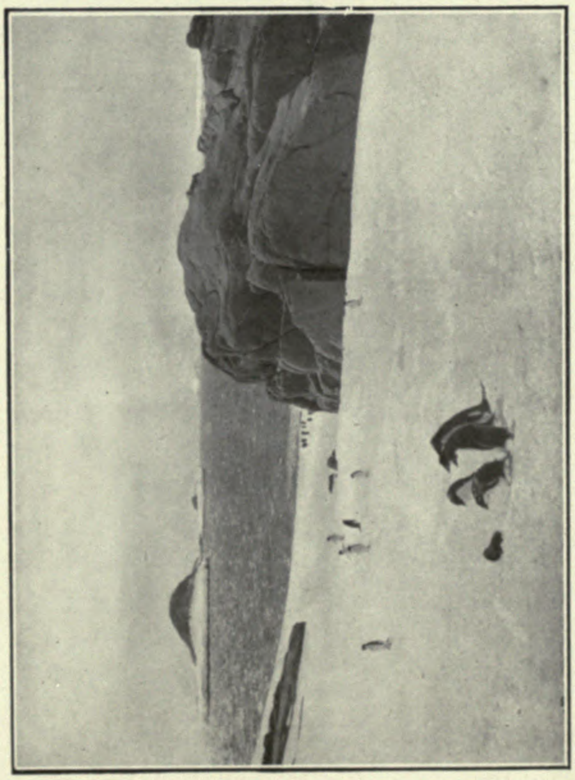
Laseron.

Fig. 1.



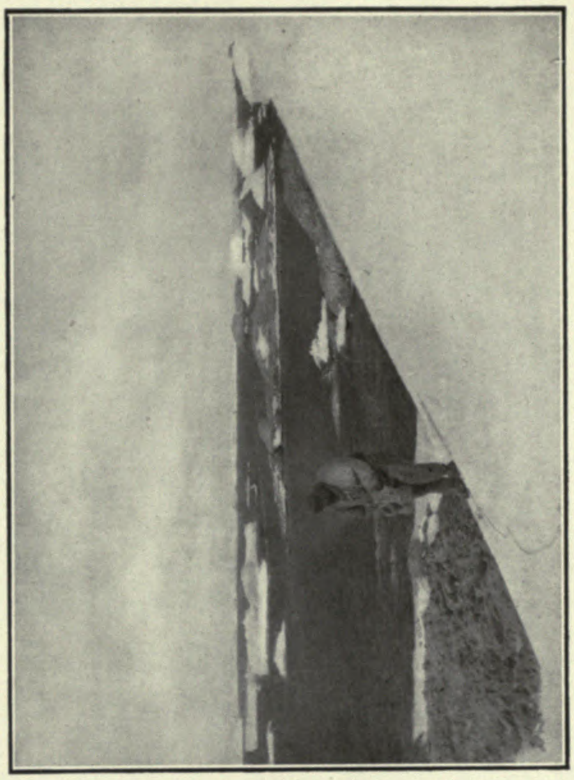
Laseron.

Fig. 2.



Laseron.

Fig. 3.



Laseron.

Fig. 4.

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PLATE XXVI.

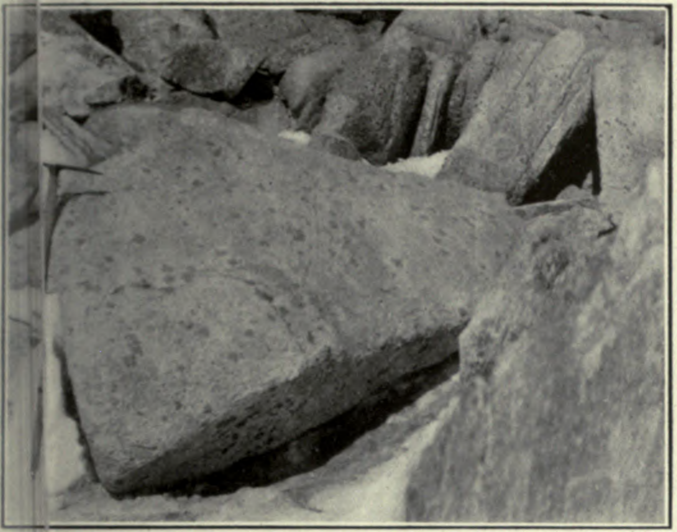

Fig. 1. *Laseron.*

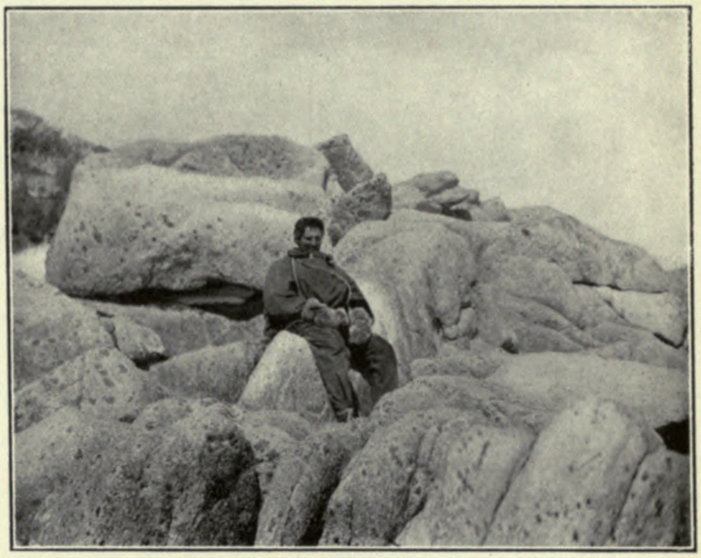

Fig. 2. *Laseron.*

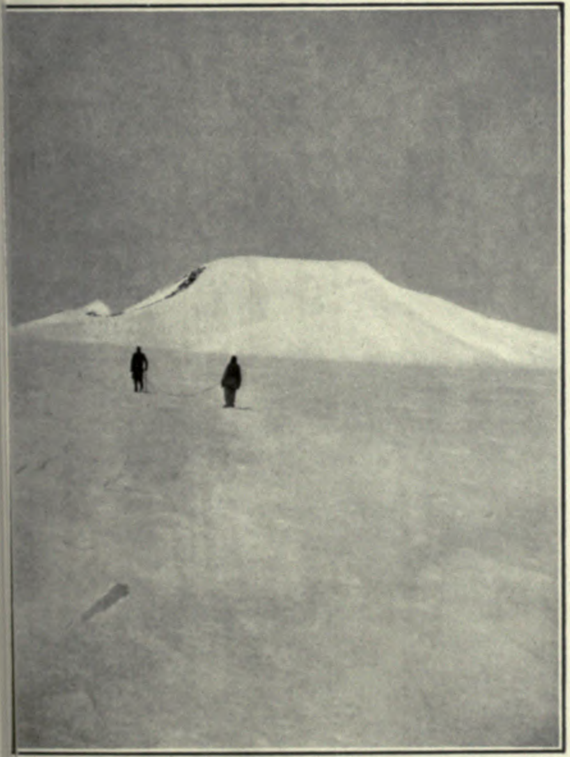

Fig. 3. *McLean.*

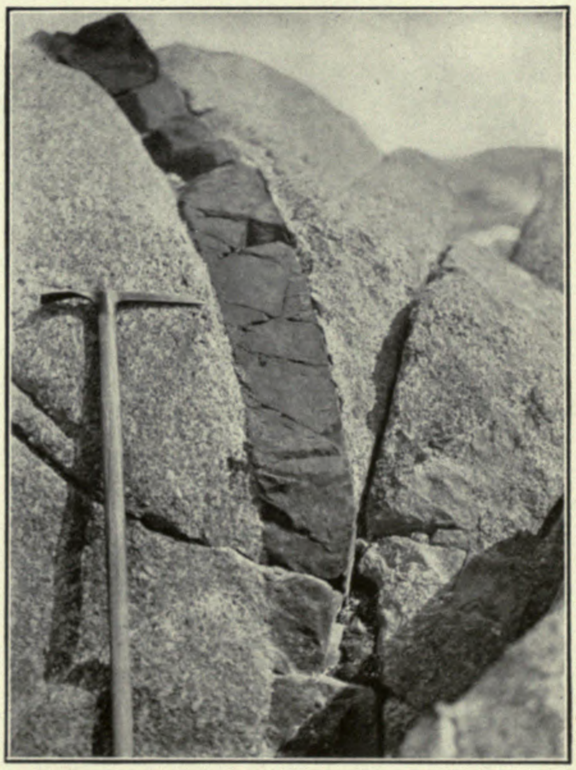

Fig. 4. *Laseron.*

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PLATE XXVII.

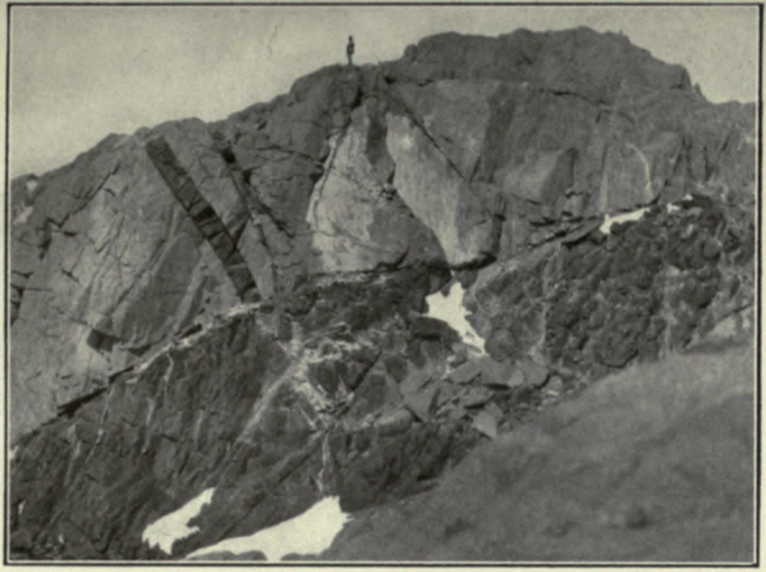

Fig. 1. Laseron.

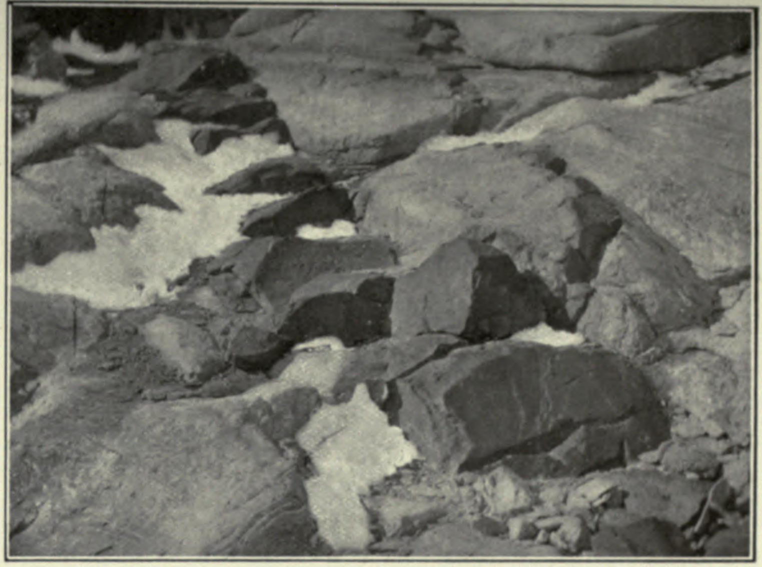

Fig. 2. Laseron.

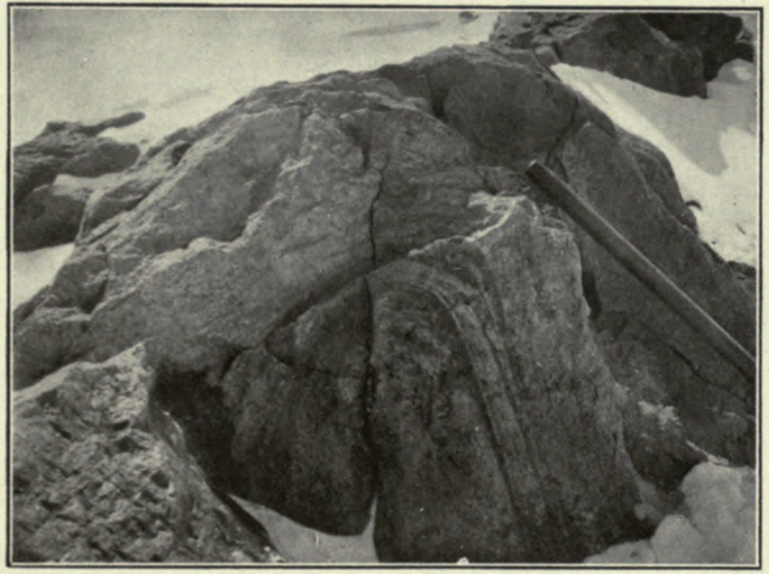

Fig. 3. Laseron.

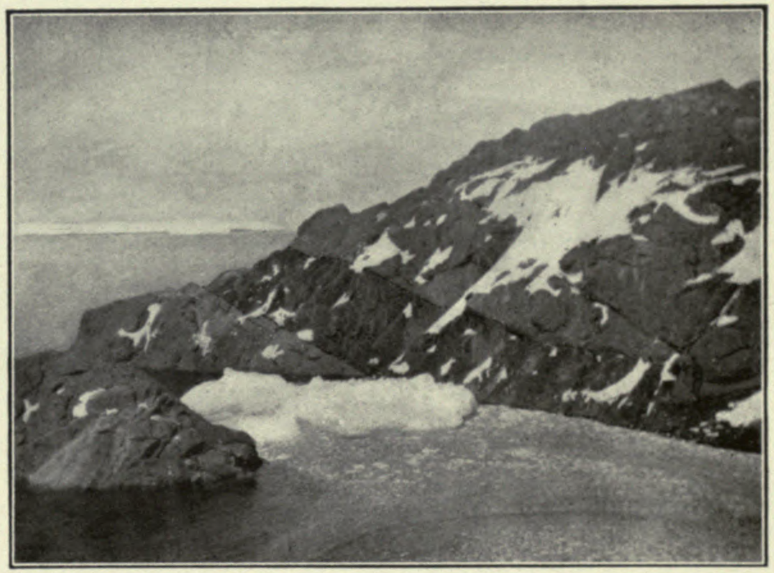

Fig. 4. Laseron.

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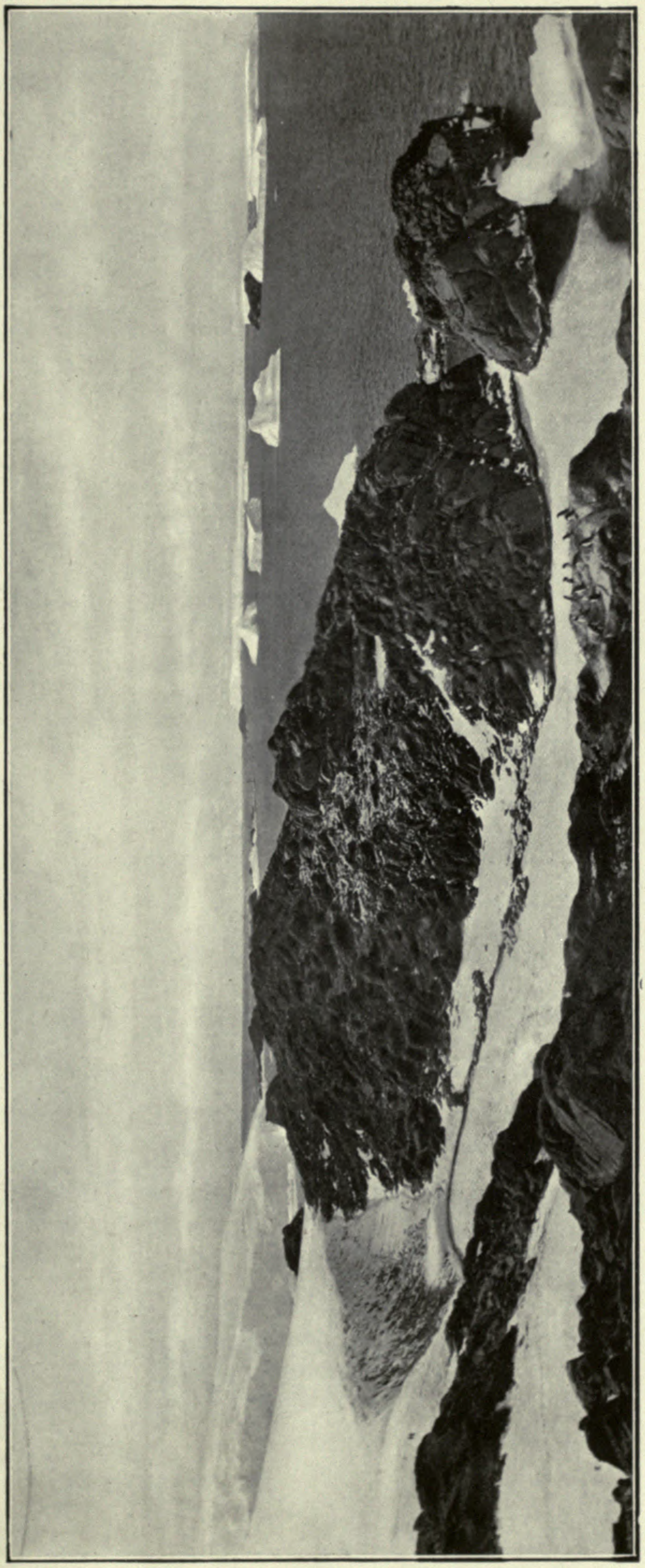
PLATE XXVIII.



Laseron.

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PLATE XXIX.

Hurley.

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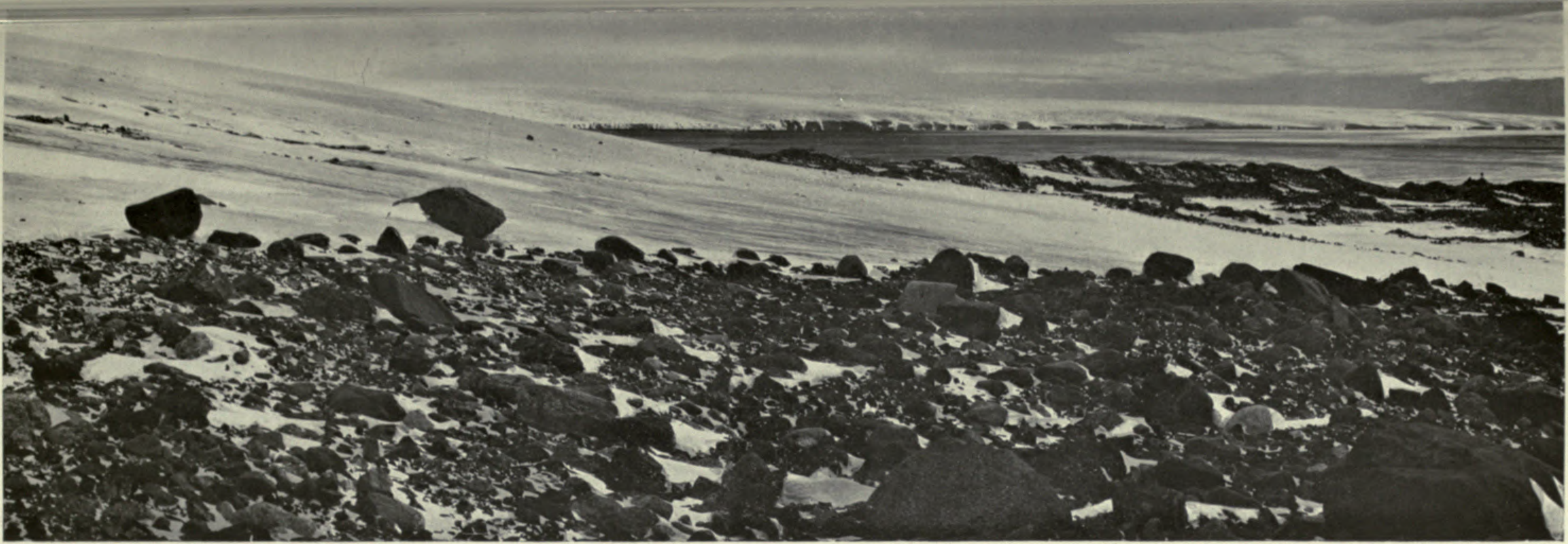

Fig. 1.

Hurley.

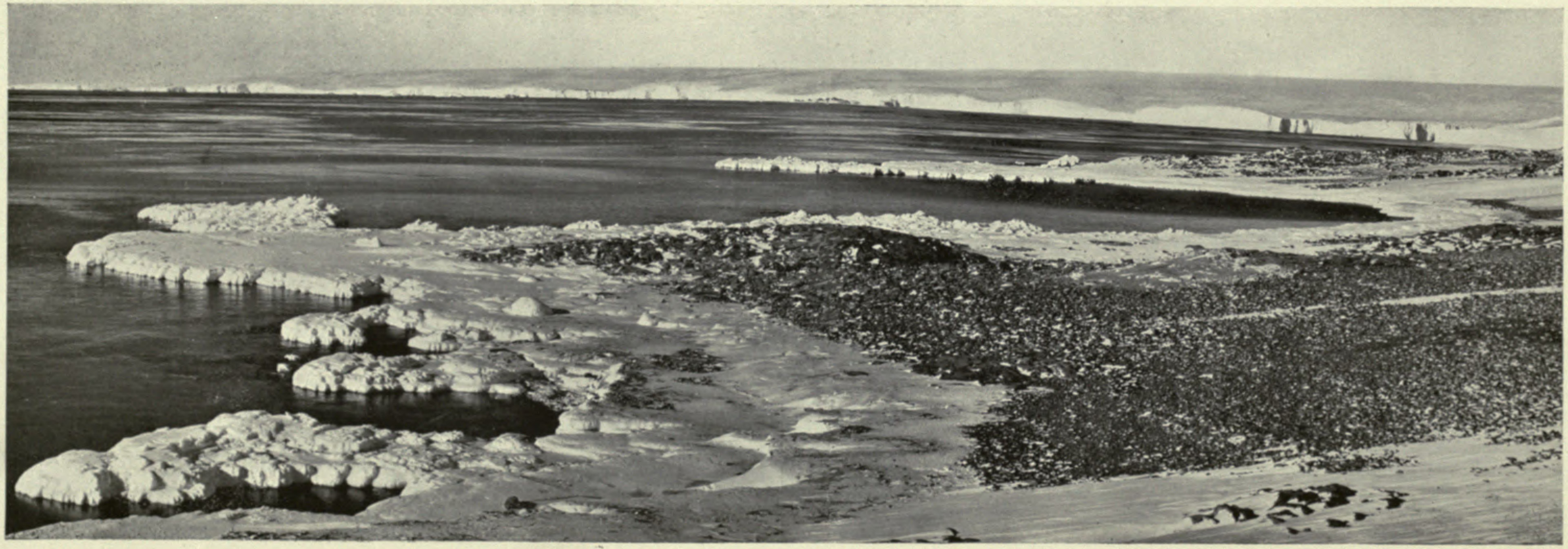

Fig. 2.

Hurley.

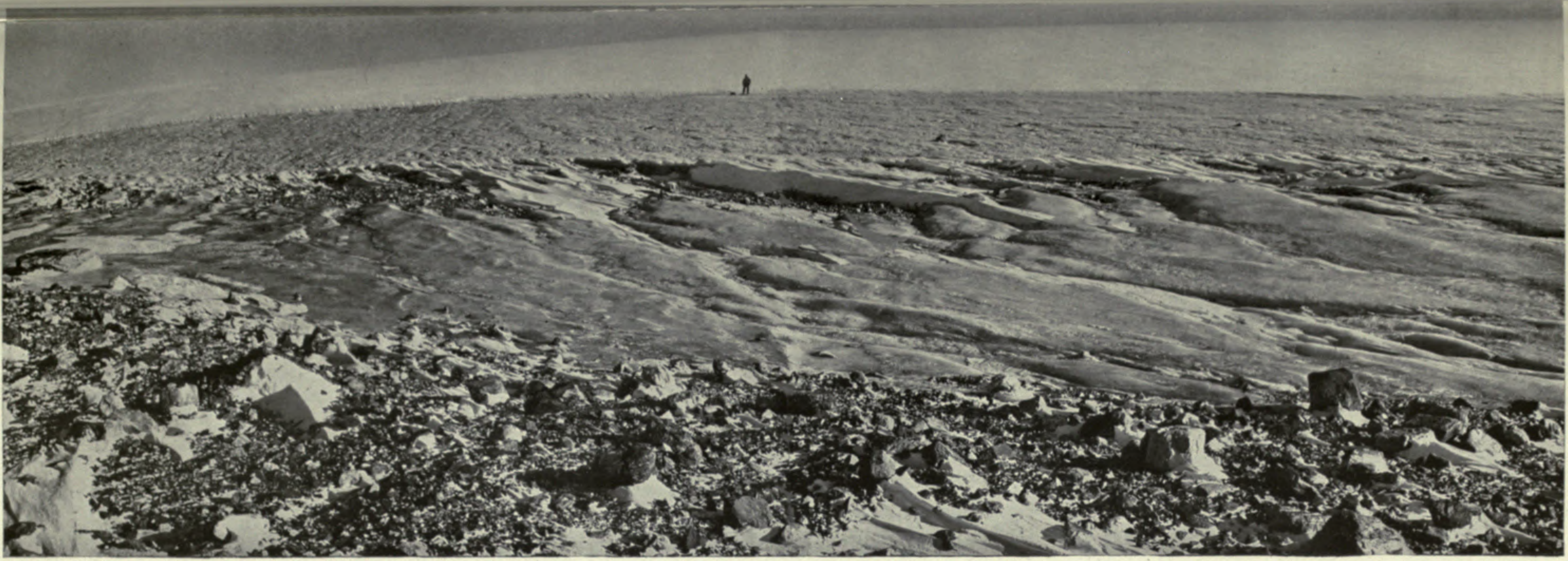

Fig. 1.

Hurley.

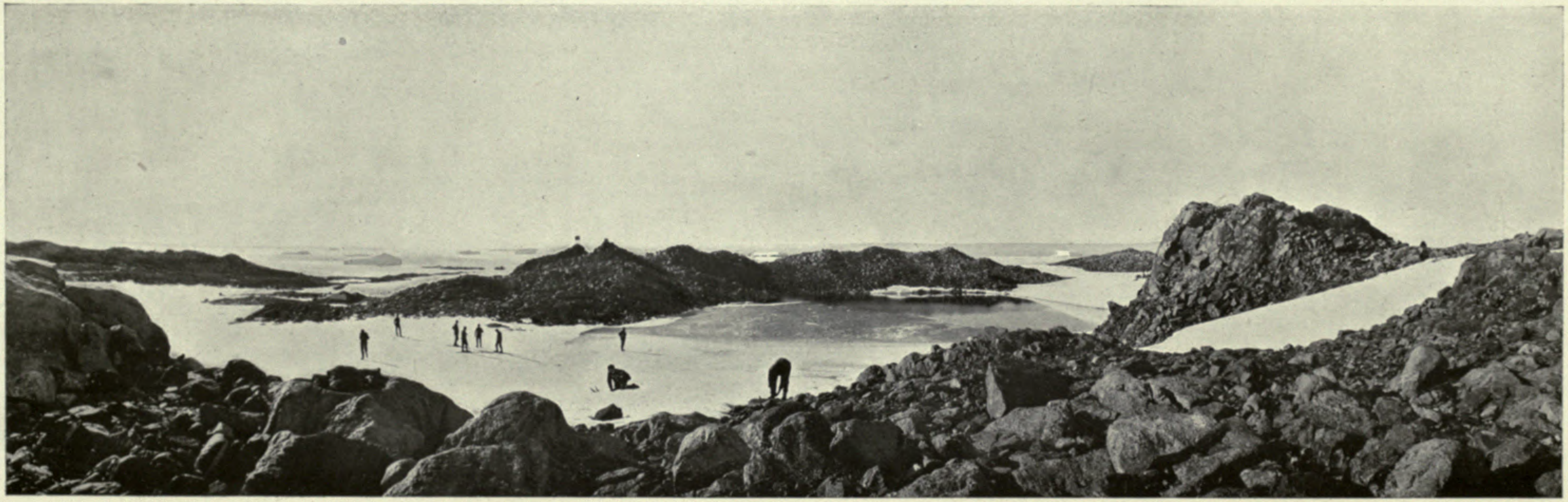

Fig. 2.

Hurley.

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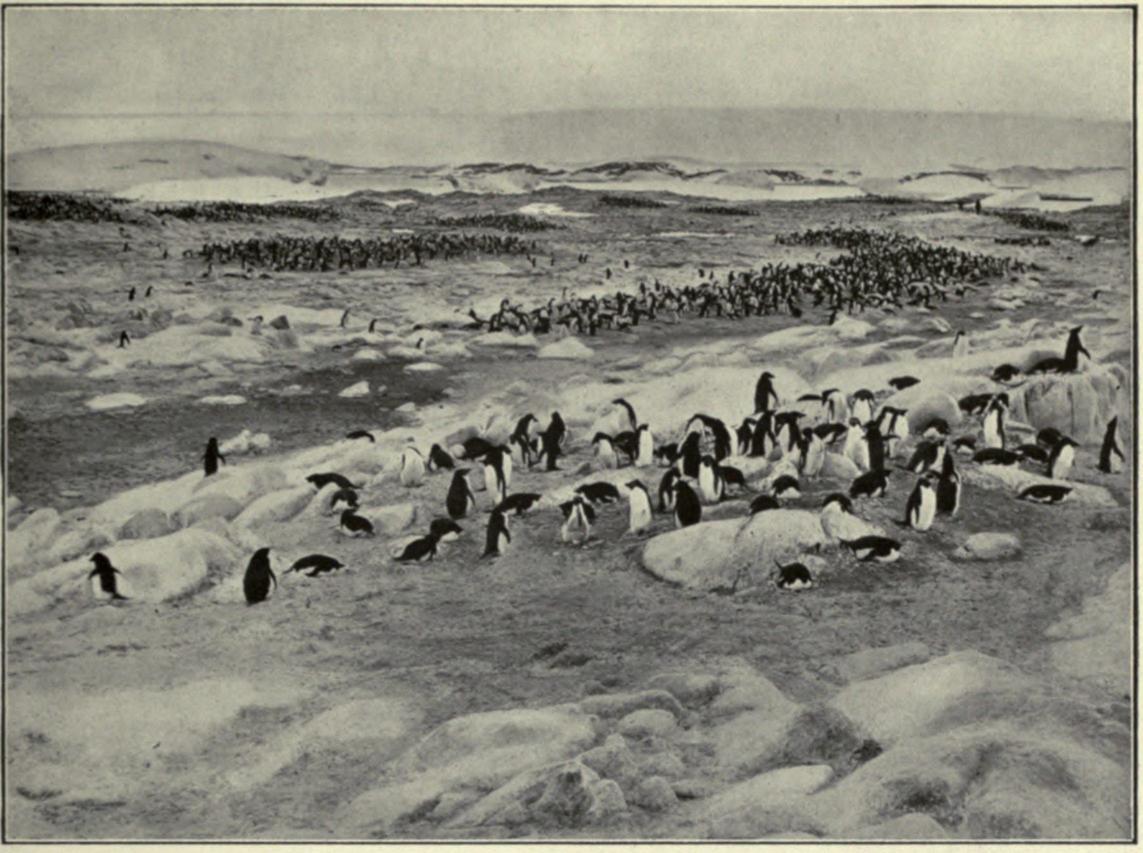

Fig. 1. *Hurley.*

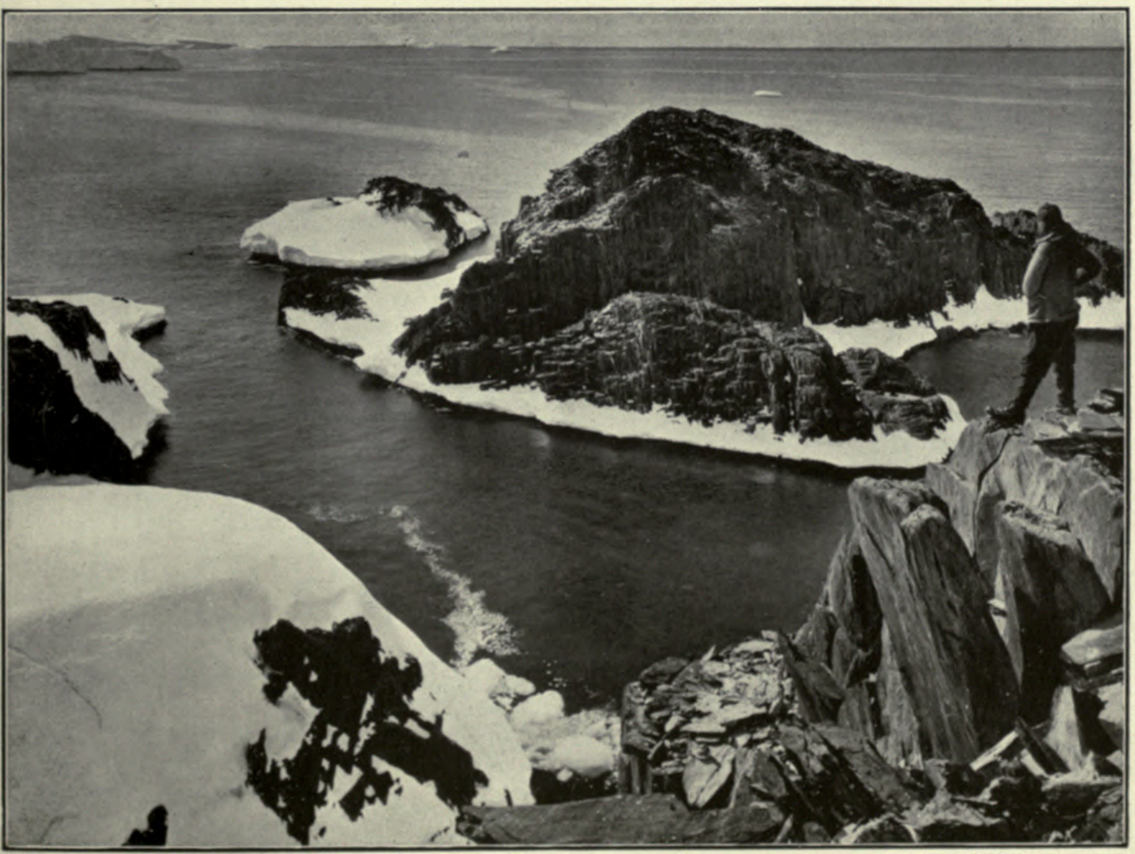

Fig. 2. *Hurley.*

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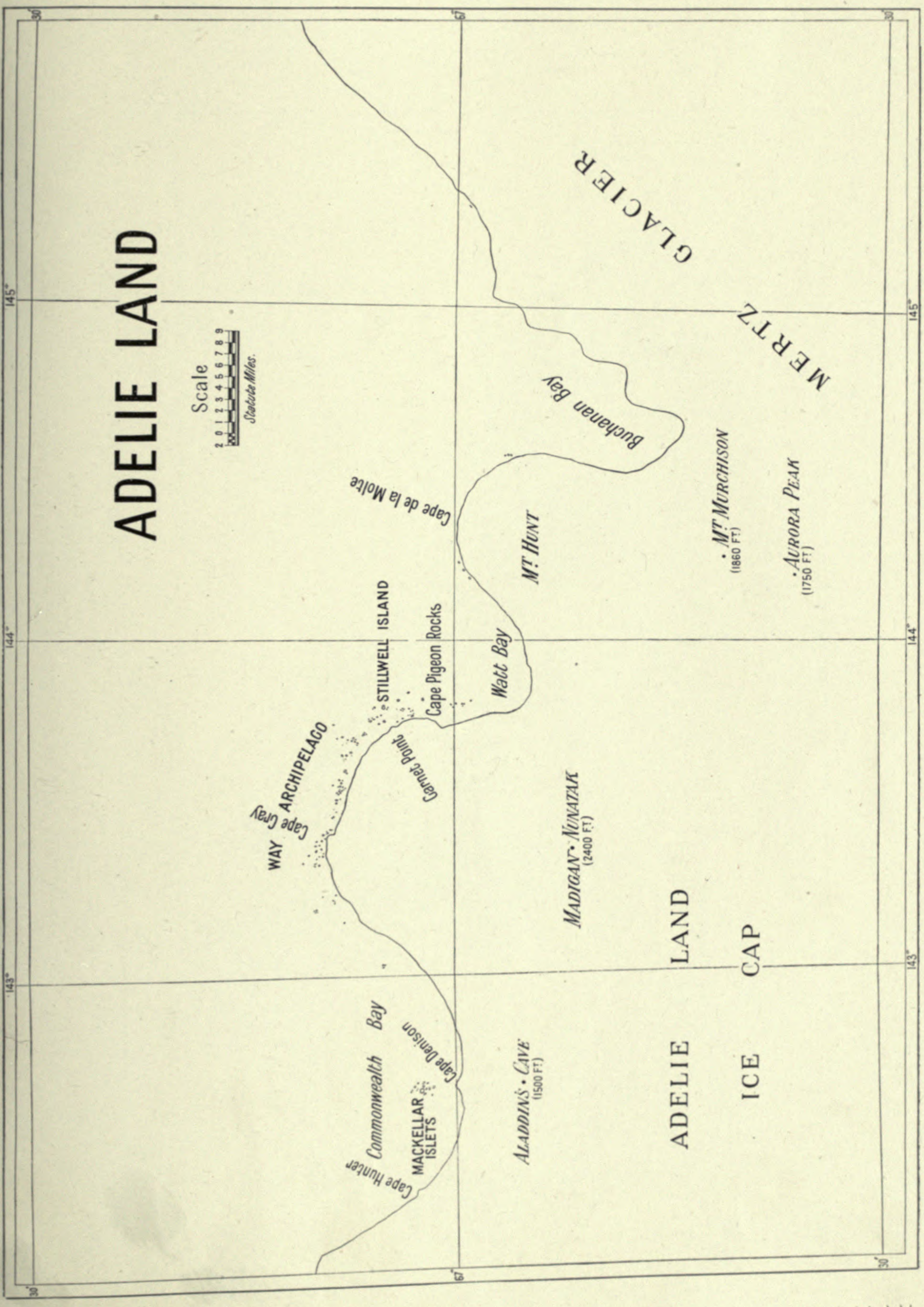
ADELIE LAND
Scale
2 0 1 2 3 4 5 6 7 8 9
Statute Miles.
145°
144°
143°
67°
30'
GLACIER
MERTZ
Buchanan Bay
Cape de la Molte
MT. MURCHISON (1860 FT)
AURORA PEAK (1750 FT)
MT. HUNT
STILLWELL ISLAND
Cape Pigeon Rocks
Watt Bay
WAY ARCHIPELAGO
Cape Gray
Garnet Point
MADIGAN NUNATAK (2400 FT)
ADELIE LAND ICE CAP
Commonwealth Bay
Cape Denison
MACKELLAR ISLETS
Cape Hunter
ALADDIN'S CAVE (1500 FT)

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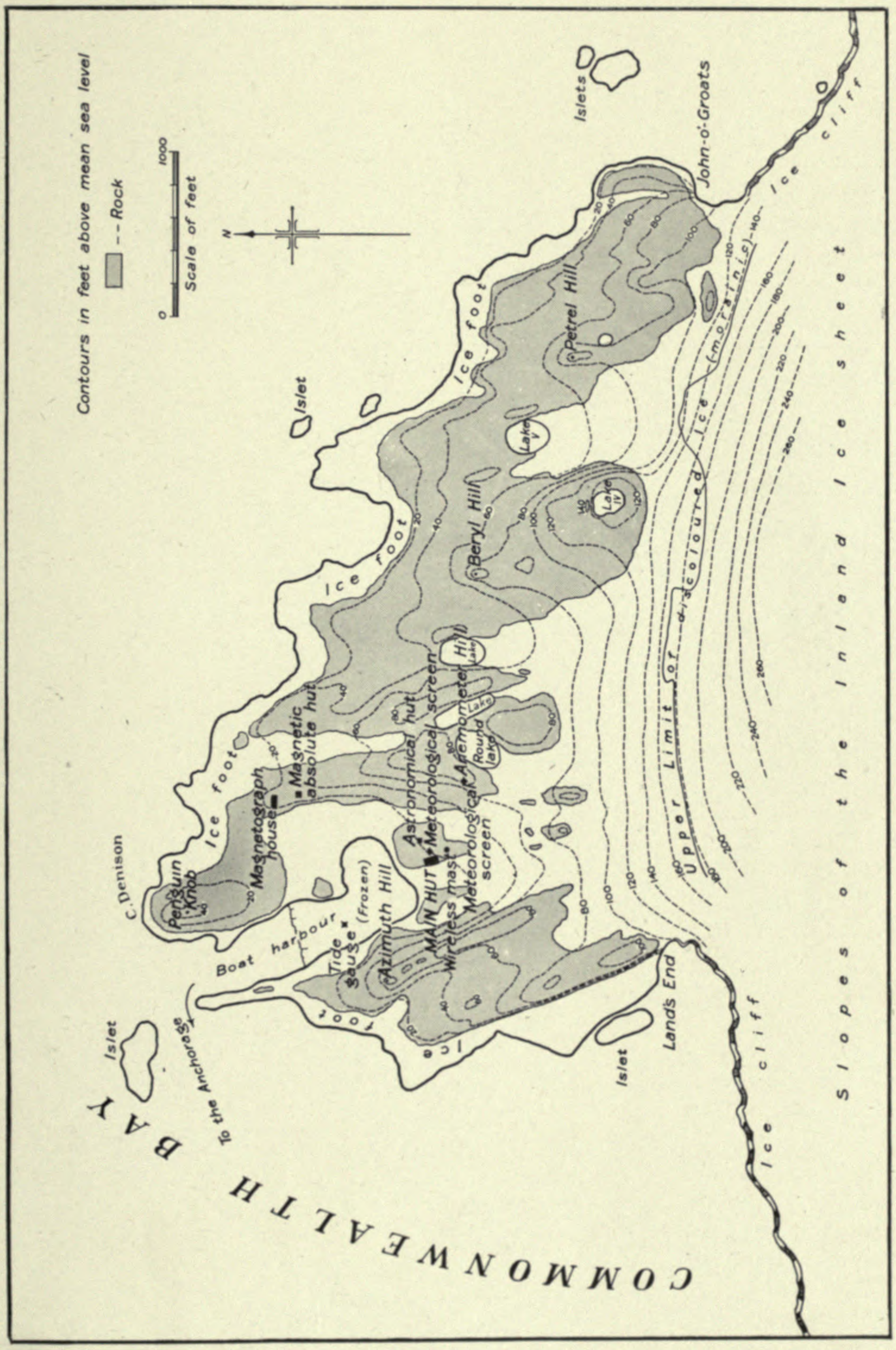
PLATE XXXV.


Contours in feet above mean sea level
-- Rock
Scale of feet
0
1000
N
Islets
John-o'-Groats
Ice cliff
Slopes of the Inland Ice sheet
Upper Limit of discoloured ice (morainic)
Petrel Hill
Lake V
Lake IV
Beryl Hill
Islet
Ice foot
Magnetic absolute hut
Magnetograph house
Penguin Knob
C. Denison
Astronomical hut
Meteorological screen
Anemometer Hill
Lake
Round lake
MAIN HUT
Wireless mast
Meteorological screen
Azimuth Hill
Tide gauge
(Frozen)
Boat harbour
To the Anchorage
Islet
Lands End
Islet
Ice cliff
COMMONWEALTH BAY

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AUSTRALASIAN ANTARCTIC EXPEDITION
1911-14.

UNDER THE LEADERSHIP OF SIR DOUGLAS MAWSON, KT., D.SC., B.E.

SCIENTIFIC REPORTS.
SERIES A.
VOL. III.
GEOLOGY.

PART II:

THE METAMORPHIC LIMESTONES OF COMMONWEALTH BAY, ADELIE LAND.

BY
C. E. TILLEY, B.Sc.

WITH TWO PLATES.

PRICE: ONE SHILLING AND SIXPENCE.

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Hon. Editor: Prof. Sir DOUGLAS MAWSON, Kt., D.Sc., B.E., University of Adelaide

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I. INTRODUCTION.

The group of rocks which are described below represent a collection of erratics made from the moraines at Cape Denison, Adelie Land. With reference to their occurrence, Sir Douglas Mawson states [1] :—

> "None of them were met *in situ*; but the evidence of their occurrence in certain moraines (their distribution), and the evidence of the rock types which do actually outcrop *in situ* on that coast of Adelie Land, point to the calc-silicate series being located under the ice Cap to the south-west of Cape Denison, probably in the depression at the head of Commonwealth Bay, between Cape Denison and Cape Hunter. This is rendered more likely, since this calc-silicate series would

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[1] Personal communication.

erode more rapidly than the tougher schists and gneisses which appear in the visible outcrops thereabouts. There is no doubt that the rocks of this series represent phases of alteration of the same sedimentary series. The alteration has been effected, it would appear, by the intrusions of extensive granitic magmas now appearing as gneiss typically developed at Cape Denison and the Mackellar Islets."

The carbonate sediments from which these rocks have been derived were characterised to a greater or less degree by the presence of detrital material, which in the process of metamorphism has reacted with the carbonate minerals. This group of rocks, however, with two exceptions, still possesses a content of free carbonate mineral. Its quantitative amount is dependent in some cases on the degree of metamorphism of the rocks concerned, and in others on the quantity of foreign material present in the original sediment, capable of chemical reaction with calcite or dolomite. Amongst these rocks, there is no example which suggests any extensive addition of material from magmatic sources, other than purely volatile constituents.

According to their mineralogic content, these rocks may be divided into the following classes :—

(1) Forsterite-Marbles.
(2) Tremolite-Marbles.
(3) Diopside-Tremolite-Marbles.
(4) Pyroxene-Garnet-Marbles.
(5) Pyroxene-Epidote-Marbles.
(6) Epidote-Marbles.
(7) Carbonate-free Calc-silicate Rocks.

The description of these various classes can now proceed *seriatim*.

II. PETROGRAPHY.

(1) FORSTERITE-MARBLES.

The rocks characterised by the presence of magnesian olivine, comprise the following :—Nos. 135, 137, 307, 318, 392, 395, 402, 653, 992, 993, 994.

As a class, they are medium-grained, white to grey rocks. The majority are characterised by the presence of yellowish-green pseudomorphs of serpentine after forsterite, and these project on weathered surfaces. In No. 395, serpentine veins the rock in two parallel bands, in the centres of which narrow venules of chrysotile asbestos are developed. Nos. 135 and 137 are characterised by the presence of orange-coloured crystals with vitreous lustre, and these on examination prove to be chondrodite. In No. 135, this mineral is largely developed along a plane surface. Flakes of light-coloured mica are sparingly distributed in a number of these rocks.

It will be sufficient to describe the nature of the minerals of these rocks as a whole, points of particular interest shown by any of them being refererd to in the course of this description.

The constituent mineral are *dolomite, calcite, forsterite, chondrodite, spinel, hornblende, diopside, phlogopite, serpentine*, and *magnetite*.

The minerals which characterise the class are dolomite, calcite and forsterite, the remainder forming a subordinate group, which, while often abundant, yet rank as accessory constituents to the class.

Dolomite.—While the ordinary method of differentiation between this mineral and calcite is the staining method of Lemberg, yet the criteria which have been found to operate in metamorphosed dolomites of other regions are often of use here. These include the different types of twinnning shown by dolomite and calcite respectively, and the degree of turbidity.

As earlier noted (1) the dolomite twinning on the $02\bar{2}1$ plane is sufficiently distinctive in favourable sections, and the turbid character of the calcite also affords a further means of discrimination. This polysynthetic twinning in dolomite suggests that a secondary twinning along a glide plane is involved.

Calcite is quite frequently twinned in these rocks and the turbidity often observed is due to the presence of minute inclusions which are probably carbonaceous.

Forsterite.—The usual habit is in rounded grains or prismatic crystals, in which the trace of the 010 cleavage parallel to the elongation is imperfectly developed. In rocks Nos. 137 and 318 the olivine is almost completely free from decomposition, but in the remainder all stages of serpentine development are revealed. Usually this is a colourless type, but in some cases it appears of a pale yellowish green tint. In No. 992 the serpentine is accompanied by granules of secondary magnetite. Where developed as an inclusion in the serpentine, the carbonate is usually calcite.

Chondrodite.—Orange yellow crystals of a member of the humite group of minerals are developed in rocks Nos. 135 and 137. In No. 135 they are partly arranged along a plane through the rock, as if indicating the passage of fluorine bearing vapours along a bedding plane or other surface of interruption.

In thin section the mineral is noticeably pleochroic, varying from golden yellow (X), to colourless (Y, Z). Twinning is faintly developed in some sections. The extinction measured from the 001 cleavage, the plane of lamellar twinning, corresponds to that of chondrodite in the section available, reading 20 degrees. Clinohumite is thus excluded.

There is no trace of intergrowth with forsterite, and serpentinisation proceeds in the same manner as in normal olivine.

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[1] Geol. Mag., Vol. lvii, 1920, p. 453.

Spinel.—The spinel of these rocks is usually the colourless magnesia spinel developed in rounded grains or more rarely subidioblastic with octahedral outline. It occurs isolated in the carbonate minerals or may be intimately associated with forsterite, occasionally enclosed in the outline of the latter.

In No. 992, the spinel has the green colour of the pleonaste type, and is there associated with magnetite which is developed peripherally and along cracks. It is usually quite free from alteration, but in some examples has developed a peripheral ring of colourless serpentine.

Hornblende.—A colourless amphibole is sometimes abundantly developed in these rocks. This is especially the case in rocks No. 318. In this rock, the hornblende is developed as subidioblastic crystals enclosing grains of forsterite, and also as narrow corona-like rims to the same mineral. The mineral shows the typical amphibole cleavages, and cross-sections show the emergence of an optic axis, with the optic axial plane bisecting the obtuse intercleavage angle. These grains are optically positive, and there can be no doubt that the mineral is edenite, and not the normal tremolite. Moreover the extinction angle exceeds the value for this latter type. Tremolite is, however, not absent from these rocks, but is sparingly developed.

Diopside is present as an accessory constitutent in clear colourless grains, with prismatic habit. In No. 395 it is present with tremolite fringing a band of serpentine. There is no definite evidence however to suggest that the serpentine has a pyroxenic derivation. The bands in this rock, with their accompanying chrysotile venules are essentially of forsterite derivation.

Phlogopite.—The colourless mica which is a frequent member of these rocks is a type with very small optic axial angle, approaching uniaxiality, being the magnesia-rich phlogopite variety common to metamorphosed dolomites.

(2) TREMOLITE-MARBLES.

This class includes the following rocks: Nos. 306, 306a, 355, 406, 673, and 707. The distinct habit of crystalline schists is given to these rocks by the abundant development of fibrous amphibole. They are grey to green-grey rocks in which the amphibole is present in light-green fibres often with a parallel orientation. This, however, is not a constant feature, the porphyroblasts of tremolite being developed as in No. 406 in diverse orientations.

A radiate arrangement appears in the lighter-coloured rock No. 707. On weathered faces the more resistant amphiboles usually project from the general surface.

The constituent minerals are *dolomite*, *calcite*, *tremolite*, *phlogopite*, *biotite*, (*chlorite*), *magnetite*, and *apatite*.

Dolomite is again revealed by the characteristic type of twinning, and both it and the calcite are universally twinned on a polysynthetic scale.

Tremolite is a general constituent in idioblastic prisms, with positive elongation, negative sign and large optic axial angle. It is colourless in thin section, but macroscopically may develop a pale-green tint indicative of the presence of the actinolite molecule.

Phlogopite is colourless to pale yellow-green, and slightly pleochroic and always with a very small optic axial angle.

Brown *biotite* is present in No. 355, and shows peripheral alteration to a light-green chlorite. The phlogopite molecule is probably present in solid solution in its constitution. It is associated with highly refracting and birefringent prisms of rutile, which are of secondary origin, and result from its degradation. The remaining constituents of these rocks call for no special remark.

(3) DIOPSIDE-TREMOLITE ROCKS.

Two rocks are strictly included within this class, Nos. 303 and 657. No. 651 may be considered here for while tremolite is absent, calcite and diopside are the chief constituents.

No. 303 is a coarse-grained grey rock with large crystals of diopside measuring up to 1 inch or more in length. It is associated with light-green fibrous amphibole. Pink-coloured calcite is sparsely distributed, and quartz can also be recognised macroscopically.

No. 657 is a finer grained rock in which on weathered surfaces, the new-formed silicates project. As such, can be recognised biotite, mica and green diopside.

No. 651 is a flesh-coloured crystalline marble containing porphyroblasts of light-green diopside.

The constituent minerals of these rocks are *calcite*, *diopside*, *tremolite*, *actinolite*, *biotite*, *plagioclase*, *titanite*, *zircon*, *apatite*, and secondary white *mica*. Dolomite has not been recognised in thin sections by the twinning, nor in those sections examined by staining. In No. 651 all carbonate can be decomposed in dilute hydrochloric acid.

The colourless *pyroxene* of No. 303 shows a lamellar twinning, and parting planes parallel to the 001 and 100 faces. The extinction angle $Z \wedge c$ is 41°. In No. 657 the pyroxene is a colourless to pale green type. The colourless *tremolite* of No. 303 is fibrous parallel to the c axis and is wedged between larger crystals of diopside. The amphibole of No. 657 is distinctly coloured and pleochroic in light-green tints. Tremolite in this rock is also a constituent of pseudomorphous assemblages of white mica and zoisite, which in some cases can be shown to take the place of plagioclase felspar.

Plagioclase is developed in rounded grains, sometimes with twinning lamellæ after the albite and pericline laws. The more basic types are the less stable, giving rise to pseudomorphs in which mica and zoisite are important constituents. There are rounded grains whose refractive index approximates to that of canada-balsam, and appear to be near oligoclase in composition.

Biotite is present in flakes showing a brown to pale-yellow pleochroism.

A crystal of a mineral showing parallel intergrowth of several individuals with good crystal outline, is developed in this rock. It is pleochroic in bluish-green to yellow-green with brown tints, is optically negative, and an optic axial plane perpendicular to the elongation, the sign of which is negative. The pleochroic tints are those of soda amphiboles, and the extinction is oblique (14 degrees). The position of the optic axial plane cannot be the symmetry plane, however, if prismatic habit obtains. The only metamorphic soda amphibole in which the optic plane is perpendicular to the 010 face is crossite. In the absence of further sections, no definite determination is possible.

(4) PYROXENE-GARNET-MARBLES.

Under this class come the rocks Nos. 658, 730, and 849. They are essentially types which would be grouped under the term "Kalksilikatgneise" by German and Scandinavian petrographers.

No. 658 is a dark-coloured banded rock, consisting of layers of pink calcite in which silicate minerals are sparingly distributed, alternating with bands rich in greenish-black pyroxene, white felspar, and thin layers of brown garnet.

No. 730 is also a banded calc-silicate-gneiss, showing layers of flesh-coloured calcite containing greenish-black pyroxene, and porphyroblasts of garnet intimately associated with epidote. Such a band is separated from finer-grained bands rich in felspar and pyroxene, by narrow layers of pyroxene and epidote.

No. 849 shows large grains of dark-brown garnet, pyroxene, and yellowish-green epidote in addition to calcite and colourless silicates.

These banded rocks with varying mineralogical composition attest the changing composition of the original carbonate sediment during its deposition.

The constituent minerals of these rocks are *calcite, pyroxene, garnet, epidote, scapolite, microcline, titanite, actinolite, quartz, apatite, magnetite and plagioclase.*

The pyroxene of No. 658 is green in colour and noticeably pleochroic: X = yellow-green, Y and Z = sea-green. The value of the extinction $Z \wedge c > 48$ degrees, and this figure when considered with the colour of the mineral in thin section indicates that the hedenbergite molecule must dominate, but that a content of sesquioxides is also present. The pyroxenes of Nos. 730 and 849 are also green in thin section, and have a high extinction-angle corresponding to a content of hedenbergite. The *garnet* of these rocks has a clove-brown colour very similar to that of the associated titanite. It is not idioblastic, and is often moulded on the green pyroxene. It is always isotropic. In No. 658 it is associated with green pyroxene, and may enclose the other minerals. In No. 730 it usually forms a core to the epidote-garnet aggregates, the central garnet being enclosed by a narrow corona of pleochroic epidote, From its associations the garnet would be expected to consist largely of the grossularite and andradite molecules. The refringence of the garnet as measured from fragments in No. 849 is somewhat greater than 1·78.

Epidote is xenoblastic. In No. 730 it is essentially a corona mineral, and is found as such surrounding garnet, pyroxene, scapolite plagioclase, and calcite. Around garnet it is often closely associated with quartz in vermicular intergrowth. In these intergrowths calcite is often included, and they correspond to the symplektitic structures of Sederholm.[1] The epidote shows a well-developed basal cleavage, and is pleohroic in yellow-green tints.

Uniaxial grains of *scapolite* of negative sign and elongation is an abundant constituent of No. 658. A typical pflaster texture is often given by this constituent. The birefringence approximates 0·03. A secondary white mica with positive elongation is a common alteration product. In No. 730 scapolite is absent and plagioclase takes its place. Rock No. 849 shows pseudomorphs after (?) scapolite, in which white mica and zoisite are the prime constituents. The birefringence of the unaltered mineral of these rocks indicates that the meionite member is predominant.

Microcline grains with noticeable cross twinning are present in association with pyroxene, and give a pflaster texture to bands which are rich in this felspar.

In No. 730 *plagioclase* is much decomposed, yielding aggregates of white mica. These grains are often surrounded by a narrow rim of epidote. Some acid plagioclase near oligoclase is interspersed among potassic felspar grains.

Quartz is a variable constituent, but is present in all three rocks. In No. 658 a number of vermicular intergrowths between scapolite and quartz are revealed (*cf.* symplektites of Sederholm).

Actinolite is developing at the expense of pyroxene in No. 849.

Titanite is a constant member of these rocks. It may be associated with garnet, but there is never any indication that it is secondarily derived from this mineral.

(5) PYROXENE-EPIDOTE-MARBLES.

Rocks Nos. 38, 310, 394, 996, and 1168 are included within this class. They are medium-grained rocks, rich in calcite (with the exception of No. 1168). On weathered surfaces, pyroxene and epidote project, the latter with the characteristic yellow-green colouration. The epidote may be developed in narrow bands through the rock. Metamorphic felspar and quartz likewise project from the general surface of the rock.

The constituent minerals are *calcite, pyroxene, epidote, microcline, scapolite, plagioclase, titanite, quartz, and actinolite.*

The *pyroxene* of these rocks is of a hedenbergitic type in Nos. 38 and 310, with noticeable pleochroism, as in the rocks of class (4). In No. 1168 the pyroxene in thin section is less strongly coloured, but the extinction $Z \wedge c$ is not less than 47° to 48°, so that the presence of sesquioxides is indicated. As a whole the pyroxenes may be regarded as hedenbergitic rather than diopsidic. A parting parallel to the 001 face is often developed (*cf.* No. 1168).

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[1] Sederholm Bull. Comm. Geol. Finl. No. 48, 1916, p. 60.

Epidote is a very characteristic mineral of these rocks, present in irregular grains and again as narrow rims to other minerals. A basal cleavage is usually strongly manifest. The extinction in sections parallel to the optic axial plane is approximately 30° from the 001 cleavage. The optic sign is negative, with the optic plane perpendicular to the cleavage. It is strongly pleochroic in yellowish-green tints, and a high content of Fe_2O_3 is indicated by a high birefringence of 0·04 (as in No. 38). Intergrowths with quartz are not uncommon.

A potash felspar with *microcline* twinning is present in variable amount, and calls for no special remark.

Scapolite is present in Nos. 38 and 310, but is absent in the remaining rocks. It has the high birefringence of the scapolites of the pyroxene garnet rocks. In No. 38 it may be surrounded by a narrow shell of basic plagioclase. In many cases this cannot be regarded as a secondary development of scapolite from plagioclase, as the boundaries are quite sharp. Rather it has the appearance of primary growth, and suggests that plagioclase appeared in place of scapolite when the supply of essential mineralisers for the formation of the latter mineral became exhausted.

Bluish-green *actinolite* is present in No. 996, but is absent in the other rocks. It forms independent crystals in the rock.

Quartz is sparingly distributed in these rocks, and very characteristically in association with epidote. Its presence here suggests that it is a by-product in the synthesis of epidote.

Two single grains of pleochroic *tourmaline* are observed in No. 996. The pleochroism scheme is $O > E$ with O = dark green and E = reddish-brown.

(6) EPIDOTE-MARBLES.

The rocks of this class are Nos. 132, 305, 308, 384, 386, 534, 654, 676, 995, 997, and 1163. As a class they are fine-grained rocks, which on weathered surfaces show an abundant development of yellow-green epidote. Some of them are banded, due to streaks and lenses of this mineral, and irregular segregations can often be observed.

The constituent minerals are *calcite, epidote, actinolite, microcline, plagioclase, titanite, biotite, quartz, chlorite, apatite* and *magnetite.*

Calcite shows abundant lamellar twinning, and the grain-size is very variable. It is especially fine-grained in rocks Nos. 305, 386, 534, and 1163. In some examples distorted twin lamellæ and mortarisation of the larger calcite grains (as in No. 997) bear witness to the shearing movements which have affected the rocks.

Epidote is present in yellowish-green crystals, which are often idioblastic, with a dominant basal cleavage. It is not infrequently disposed in layers through the rock, associated with quartz and felspar. This is strikingly seen in No. 132, where the felspar is largely microcline. The epidote is always a variety rich in ferric oxide, as is indicated by its birefringence and pleochroism. It is only accessorily present in No. 654. In No. 1163 the mineral is undergoing change to a chloritic product with anomalous interference tints.

Actinolite in pleochroic plates of blue-green to yellow-green tint is often present in association with the epidote.

Microcline, plagioclase, and quartz are the colourless silica containing minerals. The potash felspar with microcline twinning is closely associated with epidote and quartz. The twinning is, however, not a constant feature, and in the absence of cleavage and twinning, it is sometimes difficult to discriminate from plagioclase.

The *plagioclase* present in these rocks is usually of an acid type. It may possess both pericline and albite twinning lamellæ. The felspar of No. 995, for example, is an optically positive type, whose refractive index is greater than that of canada-balsam, but less than that of quartz. It corresponds to albite-oligoclase. Secondary paragonitic (?) flakes are distributed through the grains. In the other rocks the plagioclase very generally shows a refractive index less than that of quartz. The place of the more basic felspars is evidently taken by the abundant epidote.

Quartz is quite common as a constituent of the ground mass with calcite, and may sometimes vein the rock as in No. 997.

In the bands of epidote in No. 132, the associated quartz shows rows of pores along cracks, oriented at right-angles to the long axes of the bands.

Green *biotite* is present in No. 132, associated with epidote, and a single grain of highly pleochroic *tourmaline* is also to be observed.

(7.) Carbonate-free Calc-Silicate Rocks.

Two rocks which cannot strictly be defined in the classes already instituted complete the suite of rocks. Both these rocks are completely free from primary carbonate minerals. No. 1153 is a pinkish-white rock with a band of calc-silicate minerals, partly diopside and partly a dark fibrous amphibole.

Under the microscope, the calc-silicate band shows a very pale tremolitic actinolite, on the outer edge of which colourless diopside is present. This band is succeeded by a band of saussuritic material, in which secondary white mica is plentifully distributed. Quartz is abundant in streaks and lenses. It shows the effects of shearing stress in the undulose extinction and mortar texture.

No. 128 is of greater interest. The hand specimen is a greenish-grey rock, in which small porphyroblasts of felspar can be seen. In thin section the constituent minerals are observed to be felspar, epidote, and clinozoisite as porphyroblasts, whilst the ground mass is constituted of tremolite, zoisite (clinozoisite), quartz, felspar, titanite, and apatite. Epidote is present in idioblasts measuring up to 1·5 mm. in length. It shows a light yellow tint, but is seldom noticeably pleochroic. A basal cleavage is strongly developed. The double refraction does not exceed 0·027. The optic axial plane is perpendicular to the elongation and the cleavage, and the optic sign is negative. Twinning on the 100 plane is rarely developed, and is seen in sections cut parallel to the optic axial plane. The extinction is 3 to 4 degrees from the plane 100. From the basal cleavage the angle $Z \wedge a$ is 30°.

In sections nearly perpendicular to the optic axes, the interference tints are often anomalous. A few of the porphyroblasts are optically positive. These are clinozoisite. It is clear that the porphyroblasts are types comparatively poor in $Fe_2 O_3$, and grade in composition from clinozoisite (optically positive) with increasing iron content to the more birefrigent epidote (negative).

The porphyroblasts of felspar are dominantly plagioclase. They often show both albite and pericline twin lamellæ. In composition they grade from albite-oligoclase to oligoclase. Both optically positive and negative varieties are present, and the refractive index is usually equal to or greater than that of canada-balsam. The refrigence is, however, always less than that of quartz. Potash felspar is sparingly represented, optically negative and has a refringence less that that of canada-balsam.

The ground mass is constituted of quartz and alkali felspar, in which are set fibres of colourless tremolite, prisms of zoisite, and less frequently highly refringent grains of titanite and apatite. The porphyroblasts of felspar are remarkably free from the constituents of the ground mass.

III. REVIEW OF THE METAMORPHIC PROCESSES INVOLVED.

The mineralogical variation of the suite of rocks described in the foregoing is clearly resultant of two independent factors, viz. :—

(*a*) The range of chemical composition of the original sediment,

(*b*) The grade of metamorphism which the several classes have experienced.

Accepting throughout that an additive metamorphism has been inoperative, the rocks of classes (1), (2) and (3) are examples of metamorphosed dolomites. Classes (4) and (5) represent types in which a gradation to a more calcareous sediment is apparent, whilst in class (6) the metamorphosed equivalent of calcareous limestones are revealed. A varying grade of metamorphism is apparent.

The forsterite marbles bear witness to a metamorphism of essentially thermal type. The silica and alumina of detrital origin have reacted with the carbonate minerals, bringing about a partial dedolomitisation. The presence of fluorine is established by the occurrence of chondrodite. The halogen is doubtless derived from the igneous magma to which the metamorphism of these rocks is due.

In the second class of marbles, however, whilst dolomite is present with the calcite, the dominant silicate mineral is neither forsterite nor diopside, but tremolite. The habit of crystalline schists which these rocks possess suggests that in their metamorphism the element of shearing stress was dominant. Under these conditions the antistress mineral, forsterite, does not develop.

In the diopside-tremolite-marbles, dedolomitisation has been complete, and the residual carbonate mineral is calcite. With the disappearance of dolomite, the entry of magnesia-free silicate is permitted, and in accordance with this, these rocks develop subordinate plagioclase. The composition and texture of the rocks of this class allows them to be regarded as contact types.

In class (4) the pyroxene-garnet-marbles, an abundance of detrital constituents has given rise to a varied assemblage of metamorphic minerals. Microcline arises from detrital sericite, the excess alumina being absorbed in the accompanying silicates, and scapolite develops in place of plagioclase, when the necessary volatile elements are present.

The pyroxene, garnet and epidote, show by their optical properties that a not inconsiderable amount of iron is present in their molecules. The source of this iron oxide, is doubtless ferrous carbonate or hydrated iron oxide (limonite), in the original sediment. The hedenbergitic character of the pyroxene shows that portion of the magnesia is replaced by FeO.

The coloured garnet must be regarded as a grossular andradite solid solution. This is confirmed by its paragenesis, and optically by the refringence. A possible type of reaction which has led to the development of this mineral may be represented as follows :—

$$6CaCO_3 + H_4Al_2Si_2O_9 + Fe_2O_3 + 4SiO_2 = 2Ca_3AlFeSi_3O_{12} + 6CO_2 + 2H_2O.$$

Epidote must be regarded as the youngest of the silicates. The presence of the epidote-quartz symplektites around the garnet suggests that the development of epidote in these cases is attributable to a degradation of the garnet molecule in a later stage of decreasing metamorphism,

$$3Ca_3\,(AlFe)_2Si_3O_{12} + H_2O = 2HCa_2\,(AlFe)_3Si_3O_{13} + 3SiO_2 + 5CaO.,$$

the lime with carbon dioxide giving the associated calcite. A development from the anorthite member of the plagioclase has also played a part.

In the rocks of class (5) epidote is an abundant constituent, and must be given a place as a primary constituent, derived either from a reaction of carbonates and ferric oxide, with kaolin or sericite, in the latter case being accompanied by microcline. The rocks of this class resemble those of class (4) with the distinction that garnet is not represented and its place is taken by epidote.

The rocks of class (6) resemble the products of the outer zone of contact metamorphic regions. Pyroxenes are absent, and they are represented by actinolite. Epidote is the most abundant coloured silicate. The rocks are characterised by their fine grain, and both structurally and texturally they bear witness to a comparatively low grade of metamorphism. This metamorphism has been sufficient however to give rise to metamorphic felspar in association with epidote. Much of the acid plagioclase, however, must be considered as being originally developed in the rocks, for its mineralogical association with calcite or with quartz points to this conclusion. The degree of metamorphism has allowed recrystallisation, probably with increase of grain size.

In the carbonate-free rock, No. 128, the epidote and tremolite reactions have proceeded to the exhaustion of the carbonate mineral.

IV. PARAGENESIS.

In the following table, the occurrence of the various minerals in the suite of rocks is shown in their paragenetic relationships :—

	Calcite.	Dolomite.	Spinel.	Forsterite.	Chondrodite.	Edenite.	Tremolite.	Pyroxene.	Microcline.	Plagioclase.	Scapolite.	Garnet.	Epidote.	Quartz.
Calcite	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Dolomite	+	+	+	+	+	+	+	+						
Spinel	+	+	+	+	+	+	+	+						
Forsterite	+	+	+	+	+	+	+	+						
Chondrodite ...	+	+	+	+	+	+	+	+						
Edenite	+	+	+	+	+	+	+	+						
Tremolite	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pyroxene	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Microcline	+						+	+	+	+	+	+	+	+
Plagioclase ...	+						+	+	+	+	+	+	+	+
Scapolite	+						+	+	+	+	+	+	+	+
Garnet	+						+	+	+	+	+	+	+	+
Epidote	+						+	+	+	+	+	+	+	+
Quartz	+						+	+	+	+	+	+	+	+

The part played by the lime-alumina silicates is clearly shown in the paragenetic relations of such minerals as plagioclase, scapolite, garnet and epidote. In dolomitic limestones, they enter only after dolomite and the pure magnesian silicates and aluminate (spinel) have disappeared. Microcline appears in a similar fashion. Detrital sericite is first converted into the magnesian-mica, phlogopite, which is characteristically a member of the forsterite marble group of rocks. This mineral reacts later with silica and calcite giving pyroxene and microcline.

In these rocks pure magnesium-aluminium silicates do not occur. Of these latter, cordierite and pyrope garnet are the types. Cordierite is unknown amongst metamorphosed carbonate rocks, and is unstable in the presence of monoclinic pyroxene. Goldschmidt (1) considers that its absence may be attributed to a reaction of the form—

$$Mg_2A1_4Si_5O_{18}+2CaMgSi_20_6 = 4MgSiO_3 + 2CaA1_2Si_20_8 + SiO_2$$

yielding enstatite or hypersthene, as in the limestone contact zones of the Christiania region. A rhombic pyroxene is, however, wholly wanting in these Antarctic rocks, as in the product of other areas of regional metamorphism. In this respect the metamorphism in the Christiania region may be regarded as the ideal thermal type unaccompanied by any notable shearing stress (2).

In the rocks now studied, the alumina of potential cordierite is represented in plagioclase, and the magnesia in monoclinic pyroxene.( ) According to Eskola (4) garnets containing more than 75 molecules per cent. of pyrope are unknown, and even these are confined to eclogitic rocks, and unknown amongst metamorphosed dolomites. In this respect pyrope and grossularite differ widely in their paragenesis.

Throughout this suit of rocks quartz is stable in the presence of calcite. Even in the carbonate-free calc-silicate rock (No. 128) there is no development of wollastonite. The application of Nernst's heat theorem to the equilibrium—

$$CaCO_3 + SiO_2 \rightleftarrows CaSiO_3 + CO_2$$

gives a PT curve which rises with the pressure. For aluminous and ferromagnesian lime silicates the corresponding curves, as Goldschmidt (5) has pointed out, run at less elevated temperatures.

Whilst these more complex silicates (epidote, tremolite, pyroxene, &c.) were abundantly produced, the development of wollastonite—the high-water mark of metamorphism in calcareous sediments—was not attained.

---

[1] V. M. Goldschmidt, Vidensk. Skrifter, 1911, No 1, p. 138.

[2] A. Harker, Pres. Address Geo. Soc., 1918, p. LXXVIII.

[3] Geol. Mag., vol. lvii, 1920, p. 496.

[4] P. Eskola, Norsk. Geol. Tidsskr. vi, p. 172–3.

[5] V. M. Goldschmidt, Vidensk Skrifter, 1912, No. 22, p. 12.

V. EXPLANATION OF PLATES.

PLATE XXXVI.

Fig. 1.—*Calc-silicate marble.* Photo of the natural surface developed by weathering under Antarctic conditions of wind and drifting snow. The softer carbonates are removed, leaving the harder silicates standing prominently in relief. Concomitant with the metamorphism of the rock, are evidenced contortion and brecciation of the harder bands. Two-thirds natural size.

Fig. 2.—*Calc-silicate-Gneiss* (Garnet-pyroxene-Marble.) Specimen No. 658. The photograph shows alternating bands of calcite, green pyroxene and felspar, and brown garnet.

The continuous black bands are seams of grossular-andradite, and the remaining black lenses and streaks are hedenbergitic pyroxene associated with white felspar. About natural size.

PLATE XXXVII.

Fig. 1.—*Forsterite-Marble.* Specimen No. 318. The microphotograph shows calcite, dolomite, forsterite, spinel, and the aluminous amphibole, edenite.

The amphibole is typically developed as coronæ around the forsterite grains. Isolated grains with amphibole cleavage are present in the lower half of the photograph. The clear carbonate grains immediately above are dolomite. Magn. 40 diameters.

Fig. 2.—*Garnet-pyroxene-marble.* Specimen No. 658. The constituents shown are garnet, green pyroxene, scapolite, microcline, a symplektitic intergrowth of scapolite and quartz, and grains of titanite, apatite and calcite. Magn. 40 diameters.

Fig. 3.—*Garnet-pyroxene-Marble.* Specimen No. 730. The constituents are garnet, epidote, plagioclase, green pyroxene, calcite, and quartz. The garnet is surrounded by a shell of epidote, intergrown with quartz and some calcite. The large plate of plagioclase is filled with a sericitic decomposition product, and is itself bordered by a perimorph of epidote. Magn. 40 diameters.

Fig. 4.—*Carbonate-free calc-silicate* rock. Specimen No. 128. The constituents are clinozoisite, epidote, plagioclase, microcline, tremolite and quartz. The porphyroblasts of epidote and felspar are set in a ground mass of tremolite, zoisite, quartz and felspar. The felspar porphyroblasts are remarkably free from the groundmass constituents. Magn. 40 diameters.

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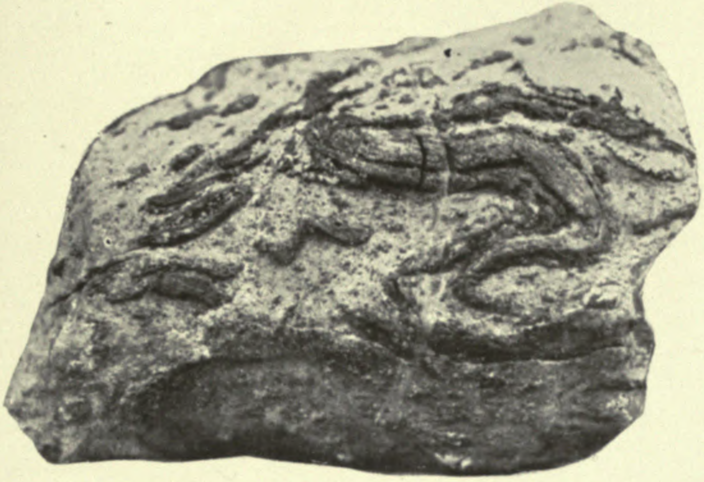

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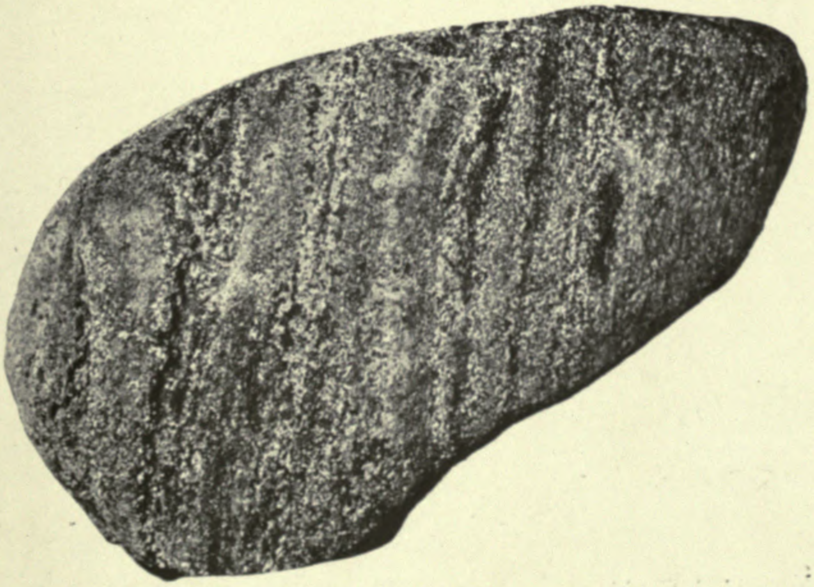

Fig. 2.

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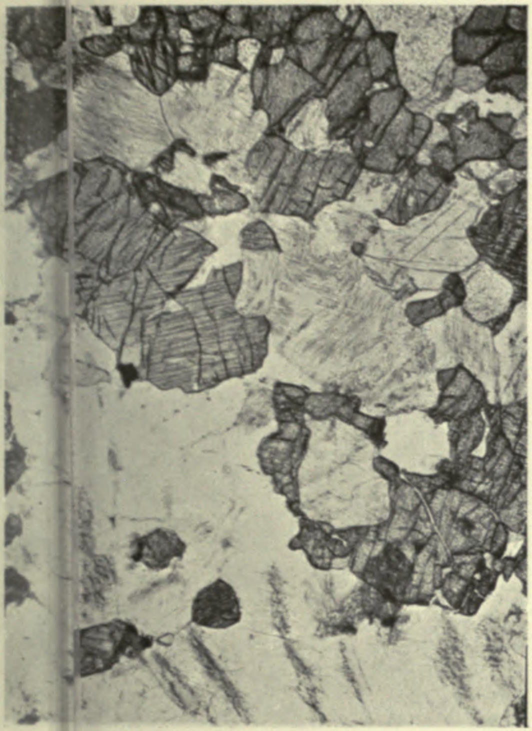

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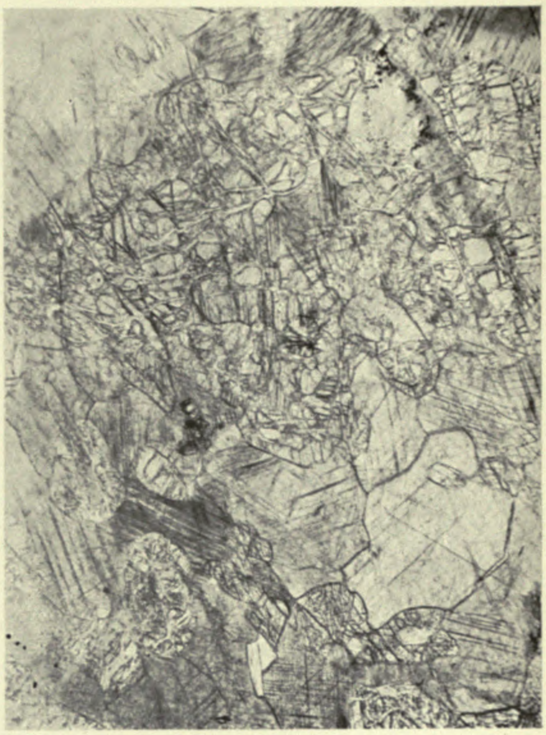

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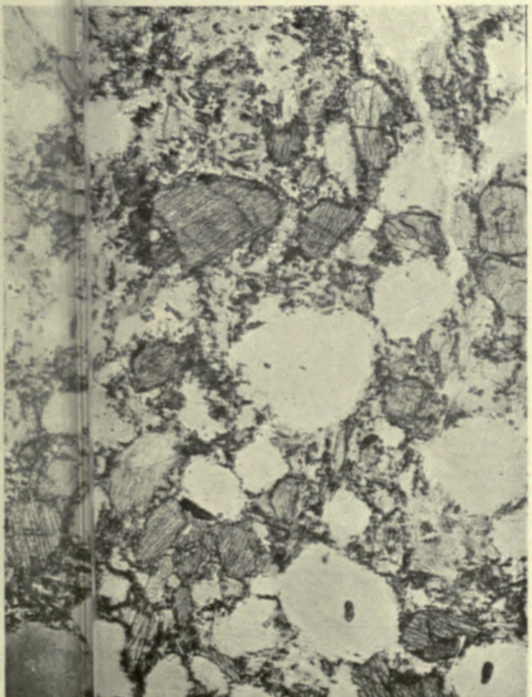

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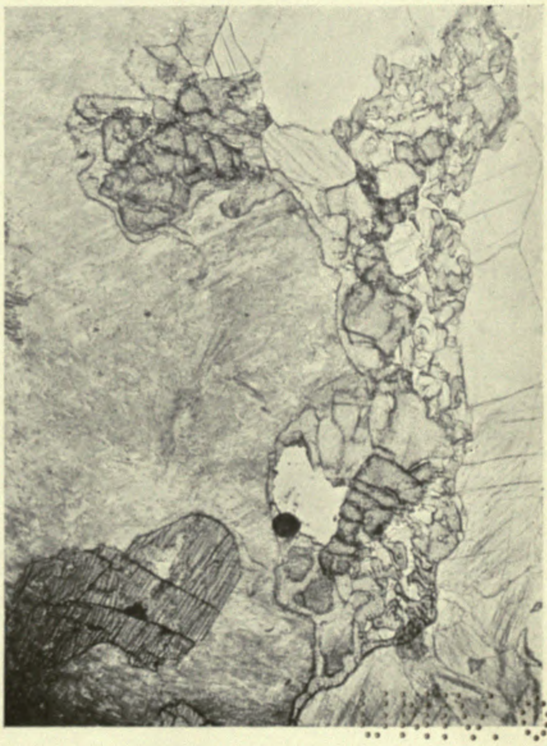

Fig. 4.

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AUSTRALASIAN ANTARCTIC EXPEDITION
1911-14.

UNDER THE LEADERSHIP OF SIR DOUGLAS MAWSON, KT., D.Sc., B.E.

SCIENTIFIC REPORTS.
SERIES A.
VOL. III.
GEOLOGY.

APR 13 1927

PART III:

THE DOLERITES
OF
KING GEORGE LAND AND ADELIE LAND.

BY
W. R. BROWNE, D.Sc

WITH TWO PLATES.

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THE DOLERITES

OF

KING GEORGE LAND AND ADELIE LAND.

BY

W. R. BROWNE, D.Sc.

(*Lecturer in Geology, University of Sydney.*)

WITH TWO PLATES.

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THE most important section of this collection of basic igneous rocks consists of three specimens of dolerite from the great sill at the Horn Bluff, King George Land. Other dolerite types related to that of the Horn Bluff sill were collected as erratics along the coast of Adelie Land, notably at Cape Denison, where the main collection of the Expedition was made.

At the Horn Bluff the great sill, intrusive into a sandstone formation, rises in organ-pipe formation as gigantic cliffs upwards of five hundred feet in height. The specimens from this important locality were collected by C. T. Madigan's party.

I. THE DOLERITES OF THE HORN BLUFF.

1. PETROGRAPHY.

The rocks present certain variations in texture, but consist essentially of the same minerals, plagioclase, pyroxene, and iron ore, with a mesostasis of micropegmatite. It will be convenient to preface short descriptions of each of these rocks with an account of the characteristics of the principal mineral constituents.

Plagioclase is as a rule fresh, but occasionally showing slight alteration to sericite. The habit is usually stout prismatic, but in the finest-grained rock (No. 732B) the prisms are more elongated. Zoning is marked, especially in the two coarse rocks (Nos. 732A and 733), and twinning is present on the albite and occasionally on the Carlsbad law, pericline twinning being visible only in the felspars of the coarsest phase (No. 733). The limits of chemical composition are bytownite ($Ab_{20}An_{80}$) to andesine ($Ab_{55}An_{45}$) in the case of No. 732A, and $Ab_{29}An_{71}$ to $Ab_{45}An_{45}$ in No. 733. The felspar of No. 732B shows less strong zoning and is about $Ab_{35}An_{65}$.

The pyroxene is almost entirely monoclinic. It is very pale-grey in colour, sometimes changing peripherally to green or brownish, and without noticeable pleochroism. Some of it is apparently ordinary augite or diopside, but much is of the magnesium-rich variety, known as enstatite-augite or magnesium-diopside, characterised by an optic axial angle which is variable, but always much smaller than that of ordinary augite, approaching 0° in the limit. Extinction angles up to 43° have been observed, but it seems as though extinction and double refraction both decline with the optic axial angle. This is well seen in No. 732A, where two pyroxene individuals often occur in parallel intergrowth, that with the smaller optic axial angle being distinguished by a slightly lighter colour in ordinary light.

In addition to the usual prismatic cleavage, there is often in both pyroxenes an extremely fine basal or salite striation, which, when combined with simple or repeated twinning parallel to (100), gives rise to herring-bone structure. This basal striation is not at all constant in its occurrence, often not extending all the way across a crystal, and being developed in irregular patches. It is often brought into prominence by local yellowish alteration of the pyroxene, with decline in the birefringence. For the most part, nothing definite was observed tending to show that this basal parting betokens twinning, as has been sometimes suggested, (*cf.* Iddings, Rock Minerals, 1906, p. 305), although in one case there was something that looked like simultaneous extinction of alternate lamellæ.

A similar very fine striation is also sometimes observed parallel to (100), and this is likewise often incomplete, and accompanied by alteration. With the development of these salite and diallagic striations, there is often local obliteration of the ordinary prismatic cleavage.

Twinning, when present, is usually of the normal type, parallel to (100), but occasional cruciform twins on (101) are observed.

An almost universal characteristic of the enstatite-augite is its undulose extinction, which is sometimes zonal in character, but generally quite irregular. This is a feature which has often been observed in the pyroxenes of the quartz-dolerites, but has not yet been satisfactorily explained. Benson remarks on something analogous in connection with the rhombic pyroxenes in the dolerites of South Victoria Land[1], comparing it with the similar appearance presented by anorthoclase, and ascribing it tentatively to submicroscopic twinning. It will be remembered that Brögger and Harker[2] believe anorthoclase to be of the nature of a cryptoperthite; and it seems possible that this peculiar form of augite, containing a large proportion of the enstatite molecule, may be a similar cryptoperthitic intergrowth of rhombic and monoclinic pyroxene, a view developed by Elsden[3].

It may be that the monoclinic pyroxene at the temperature of crystallization was able to hold in solid solution a certain proportion of enstatite, more than it could retain at a lower temperature. On cooling, therefore, the excess of enstatite was expelled and took up a cryptoperthitic relation towards the augite, and the volume change, if any, involved in this process possibly set up a state of strain and produced the undulose extinction. Alternatively if the mineral is still a true homogeneous mix-crystal, a state of internal strain may perhaps have been set up owing to a tendency on cooling for the mineral to change its system of crystallization.

The habit of the pyroxene is peculiar; there is a suppression of the prism faces and a flattening of the crystal parallel to the (100) pinacoid, so that cross-sections are rectangles with the length about four times the breadth. The prisms are perhaps rather more elongated than usual parallel to the *c* axis, and this characteristic is very marked in specimen No. 733, in the description of which it will be more particularly referred to.

The mesostasis which is present in all three of the rocks is usually of such fine grain as to render the exact determination of its constituents a matter of much difficulty. Under low magnifications it appears colourless but slightly clouded, and sometimes almost isolates the plagioclase laths projecting into it. Viewed with higher magnifications it takes in most places the form of long slender rods of plagioclase arranged in different patterns on a background of another felspar with the optical characters of orthoclase. The rods may be aggregated in groups, each consisting of three or four parallel rods, crossing each other at various angles; or sheaf-like and plumose aggregates, occasionally sprouting from the end of a plagioclase may suggest the effect of frost on a window-pane; or again, the rods may form a confused interlacing network. These phenomena are similar to those described by Osann for the Tasmanian dolerite[4] and by Benson for that of South Victoria Land.

---

[1] Report of British Antarctic Expedition, 1907–9, Geology (vol. ii), page 151.

[2] Harker: Natural History of the Igneous Rocks, page 246.

[3] The St. David's Head Rock Series, Q.J.G.S., vol. lxiv, 1908, page 288.

[4] Osann: Central. fur Min., 1907, pp. 701–11.

Elsewhere the intergrowth consists of tiny squares and rectangles and gnomons of felspar in optical continuity with the outer margins of the plagioclase laths, forming a pattern on a larger surface of orthoclase. Other patches of the mesostasis consist of graphically intergrown quartz and orthoclase, the former being recognised by the familiar triangular forms of its skeleton crystals, while again, extensions of the plagioclase laths may be graphically intergrown with quartz. This latter mineral is also found as independent interstitial grains quite evidently primary in many cases, though at times possibly secondary. On the whole, however, quartz plays a very minor part in the mesostasis.

What appears to be minutely granular pale chlorite functions occasionally as an interstitial filling in the two finest grained rocks.

Iron ores, including apparently both magnetite and ilmenite, are not very abundant. They occur mostly embedded either in the peripheral parts of the pyroxenes or else in the mesostasis.

Tiny apatite needles are pretty abundant in the mesostasis of all the rocks, but practically nowhere else, so that the total proportion of apatite in the rocks is insignificant.

Of the two specimens labelled No. 732, the finer-grained, which we may call No. 732B, was collected " 6 feet above the contact of the volcanic rock and the sandstone." The hand specimen shows very marked prismatic jointing on a small scale. The main constituents of the rock are, in volume percentages :

Plagioclase	41
Pyroxene	44
Iron Ore	1
Altered Olivine (?)	3
Mesostasis	11

The plagioclase is mostly in thin to stout laths averaging perhaps ·3 mm.; a few larger individuals apparently slightly more basic than the rest are aggregated in glomeroporphyritic fashion. Enstatite-augite is probably the dominant pyroxene, but an interesting feature is the presence of a very little rhombic pyroxene, very pale-coloured and non-pleochroic, but having negative birefringence. It generally occurs completely enclosed in augite, with which it is in parallel orientation. A very few minute flakes of biotite were detected attached to grains of pyroxene.

A peculiar feature of this rock is the presence of scattered patches of a substance, green to brownish in colour, pleochroic, with a fibrous structure and strong birefringence. The patches are streaked with carbonates and crossed with cracks containing magnetite dust. These characters suggest aggregates of talc, or perhaps iddingsite, after olivine, but this is by no means certain, especially as enstatite or hypersthene might alter in similar fashion. The outlines of the aggregates do not help much in the determination of the original mineral.

The pyroxene is evenly distributed through the rock in typical ophitic relationship to the felspar. (See Plate XXXVIII, Fig. 1.)

The specimen No. 732A was taken from the *débris* at the foot of the Organ Pipes, and is coarser than No. 732B. It is a greyish-black rock in hand-specimen, with occasional pyroxene prisms visible up to 3 mm. in length. The principal constituents are, in volume percentages :

Plagioclase	54
Pyroxene	33
Mesostasis ·	11
Iron Ores	2

This constitution corresponds pretty closely with the norm of the rock, given below, and indicates that the rock has a normative mode.

Plagioclase is in stumpy prisms up to ·5 mm., though a few larger individuals attain a length of 1·5 mm. For the most part the prisms only dent the outlines of the pyroxenes, which are often subidiomorphic, so that typical ophitic fabric is absent. Parallel intergrowths of pyroxenes with different optic axial angles are frequent. There is an absence of rhombic pyroxene, biotite, and the green and brown pseudomorphs so characteristic of No. 732B. (See Plate XXXVIII, Fig. 2.)

The third of this series (No. 733) is coarser in grain than the other two, and differs much from them in other respects. It is a brownish-coloured rock with an average grainsize of about 4 or 5 mm. The dominant characteristic is the presence of many flashing cleavage-planes of pyroxene, slightly curved at times and exhibiting quite a bronzy lustre.

The minerals present are :—

Plagioclase	33	per cent. by volume.
Pyroxene	27	,,
Iron Ore	2	,,
Mesostasis	38	,,

The plagioclase forms thick prisms varying in length up to about 6 mm. and giving almost square sections at right angles to (001) and (010). There are also smaller prisms, some of microlitic dimensions. The felspars often show magmatic resorption and embayment of their edges just like the phenocrysts of a porphyritic rock, and inclusions of the mesostasis are fairly frequent. Indeed the mesostasis is so abundant that it gives rise in places to what Iddings would have called porphyritic intersertal fabric, the pyroxene and felspar playing the part of abundant phenocrysts.

The pyroxene is all monoclinic, and, judging by the size of the optic axial angle where it can be observed, is mostly, at all events, enstatite-augite. The salite striation is extremely common, and to a less extent the diallage striation, both accompanied by a brownish decomposition product which gives rise to the bronzy lustre observed in hand-specimen, while herring-bone structure is very characteristic. The alteration associated with the striation is often so arranged as to produce a kind of hour-glass appearance in the sections. A curious feature of these augites is the frequent elongation parallel to the *c* axis, one section parallel to (010) measuring more than 6 mm. in length by about ·7 mm. Some of the crystals show a marked bending into a circular arc, with undulose extinction. This bending causes a tapering in some of the sections, which, combined with the central pinacoidal twinning-line and the herring-bone structure, produces the appearance of a goose-quill, an effect heightened by the curiously serrated edges of the crystals. This serrated effect is possibly a result of the bending of the crystals during their growth, as suggested by Iddings[1] for the curved felspars of the Obsidian Cliff rhyolite. Much of the augite is graphically intergrown with the plagioclase.

The iron ore is mostly ilmenite, in characteristic plates and skeletal forms; there is also much ilmenite and magnetite in tiny granules scattered through the mesostasis.

The rock is much stained with brownish-green and brown decomposition products, which penetrate the pyroxene peripherally and along cracks, and also discolour large portions of the mesostasis. (See Plate XXXVIII, Figs. 3, 4, and 5.)

2. Order of Consolidation.

In the finest-grained rock the felspar has very evidently crystallized first, followed by the augite. In No. 732A this is not so evident; the fabric is subophitic, but the augite is often nearly idiomorphic and only marginally indented by the felspars, as though the former had been the first to start crystallizing and had continued during part of the period of crystallization of the felspar. In No. 733 the graphic intergrowth of felspar and pyroxene indicates much simultaneous crystallization of these two minerals.

It is noteworthy that much of the iron ore has crystallized late, and that the apatite is largely concentrated in the mesostasis. This is often the case in basic rocks[2], and is in harmony with the common experience that the last or pegmatitic products of consolidation of basic magmas are often rich in apatite and iron ore.

Teall, dealing with the Whin Sill dolerite[3], has remarked on the fact that the coarse-grained phases of that rock exhibit graphic or perthitic intergrowths of their constituents. A somewhat similar statement might be made about these Horn Bluff rocks.

3. Discussion of the Petrographical Features.

These three rocks are evidently to be placed among the quartz-dolerites, although quartz does not enter very conspicuously into the constitution of the mesostasis. There is an almost complete absence of biotite and hornblende, which are common minor constituents of the typical hunnediabas and kongadiabas.

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[1] Iddings: Igneous Rocks, vol. i, p. 226.

[2] *cf.* for example Elsden, Q.J.G.S., vol. lxiv, 1908, p. 289.

[3] Q.J.G.S., vol. xl, 1884, pp. 640–57.

It is instructive to compare the mineralogical constitutions of the three rocks as given roughly by Rosiwal measurements :

	No. 732B.	No. 732A.	No. 733.
Felspar	41	54	33
Pyroxene	44	33	27
Mesostasis	11	11	38
Iron Ore	1	2	2
Altered Olivine (?)	3	...	...

The rocks are placed in order of increasing average grainsize, and it will be noticed—

(1) That the ratio of light to dark constituents increases with grainsize, and

(2) That the proportion of mesostasis has notably increased in the coarsest phase.

It should be remarked that accurate figures for the mesostasis in the other two rocks were very difficult to obtain, and that a mental note was made, before results had been calculated, that the mesostasis of No. 732B had probably been over-estimated, and that of No. 732A under-estimated at the expense of felspar. Hence there is probably an actual progressive increase in the amount of mesostasis present with the increase of grainsize.

The texture of the mesostasis is likewise somewhat coarser in No. 733 than in the other two rocks, a fact which is in harmony with the observations of Holland[1], Benson[2], and others on the quartz-felspar mesostasis of quartz-dolerites.

It is unfortunately not known from what part of the sill two of these specimens originally came. That labelled No. 732B, from 6 feet above the base of the intrusion, and exhibiting prismatic jointing, probably represents a marginal facies of the rock. No. 732A, being a bit coarser in grainsize, is probably from a more interior portion of the sill.

It would be interesting to know the precise mode of occurrence of the relatively coarse-grained type No. 733. This rock is strikingly similar in texture and constitution to a coarse phase of the Tasmanian dolerite from the Domain, Hobart, similarity extending even to the curvature of the flattened and elongated pyroxene prisms. This rock, according to Professor Sir Edgeworth David[3], occurs as *schlieren* or pegmatitic segregation veins in the normal fine-grained dolerite. In a specimen in the collection of the Geological Museum of the University of Sydney, the pyroxene individuals at times exceed an inch in length, and the mesostasis forms a large proportion of the rock.

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[1] Holland, Q.J.G.S., vol. liii, 1897, p. 408. [2] Benson, *op. cit.*, p. 155. [3] Verbal communication.

A search of some of the literature of the quartz-dolerites reveals the fact that the peculiar habit and curvature of the pyroxene has often been noted. It is true there is no mention of it, for example, in Harker's description of the Carrock Fell intrusion[1], or Elsden's account of the St. David Head Rock series[2], or in J. V. Lewis's report on the diabases of New Jersey, U.S.A.[3].

But Teall, examining the dolerite of the Whin Sill[4], noted a coarse-grained variety occurring "only where the rock attains a very considerable development," in which "crystals of pyroxene measuring an inch in length are not uncommon." The crystals are flattened parallel to (100), and the cleavage planes are "bent and undulating," pinacoidal twinning is present, also a fine basal striation, absent when the rock is fresh but present in the most altered specimens. The coarser rock occurs apparently in irregular veins, the junctions of which with the fine-grained dolerite are "remarkably abrupt."

A. H. Phillips[5] noted in the trap of Rocky Hill, New Jersey, a coarse-grained phase whose relation to the other phases is not mentioned, except that it is regarded as occupying a central position in the intrusion. The pyroxene crystals "constantly increase in length as we pass in from the border" of the intrusion; in the very coarsest varieties of the rock they measure "often an inch and occasionally 2 inches in length." A schistose arrangement was sometimes seen, and slight curvature of the long axis was observed, but this is evidently attributed by the author to the pressure which gave rise to the schisosity.

The internal characters of the pyroxenes are similar to those described for the Adelie Land rock, but the basal striation is attributed to polysynthetic twinning parallel to (001). Undulatory extinction was observed of a zonal nature.

The "plumose diabase" occurring as a phase of the trap sheet of Holyoke, Massachusetts[6], appears to be a particularly coarse-grained variant of the basalt of which the sheet is composed. The pyroxenes of this rock, up to 4 inches in length, are curved, twinned on the pinacoid, and basally striated; and in addition the vertical sections show notched or serrated edges due to "the development of unit faces." These coarse-grained patches occur as lenticular masses or *schlieren* in the trap.

The similarity on many points of the Adelie Land rock with those just mentioned is very clear, and it seems as though the characteristics emphasised, especially those of the pyroxene, are peculiar to certain pegmatitic phases of the dolerites, so that the rock No. 733 may with some degree of confidence be assigned to this category.

4. Chemical Composition and Relationships.

To indicate the chemical characters of the Horn Bluff dolerite a chemical analysis, for which I am indebted to Mr. G. D. Osborne, B.Sc., and Miss M. L. Graham, B.A., was made of the rock No. 732A, the results of which are given in column I below, the analyses of three other quartz-dolerites from Antarctica and one from Tasmania being added for comparison :—

---

[1] Q.J.G.S., vol. l, 1894, pp. 311–336. [2] Elsden, *op. cit.* [3] Annual Report of State Geologist of New Jersey, 1907. [4] Teall, *op. cit.*, p. 643. [5] A.J.S., 4th series, vol. viii, 1899, pp. 267–285. [6] Emerson, Bull. Geol. Soc. Amer., vol. 1904, pp. 91–130.

	I.	II.	III.	IV.	V.
SiO_2	53·05	54·17	54·16	53·26	52·49
Al_2O_3	16·95	14·90	15·08	15·64	16·44
Fe_2O_3	0·79	1·09	0·79	0·24	2·60
FeO	6·69	7·74	8·08	7·44	5·30
MgO	6·91	10·66	7·14	8·64	6·18
CaO	11·56	8·79	10·57	12·08	11·71
Na_2O	2·05	1·26	1·60	1·25	2·06
K_2O	0·97	0·54	1·11	0·58	1·09
H_2O +	0·49	0·53	0·36	0·41	1·42
H_2O —	0·43	0·17	0·20	0·35	0·15
CO_2	......	Trace.	Trace.	......	......
TiO_2	0·65	0·64	0·70	0·70	0·62
P_2O_5	Trace.	Trace.	Trace.	0·04	Trace.
MnO	0·07	0·15	0·14	0·11	Trace.
	100·61	100·65	99·93	100·74	100·06
Analysts	Osborne and Graham.	? Walkom and Burrows.	? Walkom and Burrows.	Prior.	Dittrich.

I.—Horn Bluff Dolerite No. 732A;

II and III.—Erratics from Cape Royds, South Victoria Land. Geology (Vol. II), British Antarctic Expedition, 1907–9, p. 157.

IV.—Erratic from Knob Head Moraine, South Victoria Land. National Antarctic Expedition, 1901–4, Natural History, Vol. I., Geology, p. 137.

V.—Enstatite-augite-bearing Diabase from Launceston, Tasmania. Osann, Central. fur Min. 1907, pp. 701–711.

An inspection of these analyses shows that of all the South Victoria Land rocks No. III is most closely related to the Horn Bluff rock, and that there is a distinct chemical resemblance between them, but that a very much closer and very remarkable agreement exists between the Horn Bluff dolerite and the Tasmanian diabase. The only points of apparent difference are in the higher Fe_2O_3 and H_2O of the Tasmanian rock, which are possibly to be attributed to surface alteration. The norms of the three rocks in question emphasise the closeness of the relationships :—

	I.	III.	V.
Quartz	1·96	6·18	4·50
Orthoclase	6·12	6·12	6·67
Albite	17·29	13·62	17·29
Anorthite	33·92	30·86	32·25
Diopside	19·01	17·50	20·83
Hypersthene	18·93	22·54	12·06
Magnetite	1·16	1·16	3·71
Ilmenite	1·22	1·37	1·22
Water	0·92	0·56	1·57

This is particularly true in the case of Nos. I and V. In the latter as compared with the former there is an increase in normative quartz and magnetite, which is offset by a decrease in hypersthene. This is due to the oxidation of the FeO into Fe_2O_3, which causes more of the FeO to be required for normative magnetite, decreasing the amount available for diopside and hypersthene, and consequently liberating SiO_2 for normative quartz.

It is interesting to note, in passing, the possible effect of slight weathering on the norm, and perhaps too on the magmatic designation of a rock. It is quite conceivable that by the oxidation of the FeO, and the consequent liberation of normative SiO_2, a rock which actually contains modal olivine may show normative quartz. Further, the diversion of this SiO_2 from the femic to the salic portion of the norm would disturb the relative proportions of salic and femic constituents and of normative quartz and felspar' putting the rock into a more salic class and a more quaric order.

In the present instance the disturbance has not been sufficient to change the magmatic position of V relatively to I, and both rocks belong to III. 5. 4. 3 Auvergnose. No. III, is placed in III.4.4.3.

CONCLUSION.

The wonderful similarity between the quartz-dolerites of South Victoria Land and those of Tasmania has been pointed out by Benson[1] and Thomson[2]. The present writer has had the opportunity of examining some of the Tasmanian rocks microscopically, and of comparing them with the Adelie Land rocks, and the resemblance is certainly remarkable. Chemical and mineralogical investigation indeed show that the rocks at present under discussion are very closely related to those of Tasmania, and that they are, beyond reasonable doubt, co-magmatic with the dolerites of South Victoria Land encountered by the Scott and Shackleton Expeditions.

II. DOLERITE ERRATICS FROM THE MORAINES, CAPE DENISON.

The collections made from the moraines near the Winter Quarters at Commonwealth Bay have yielded a number of specimens that have features in common with the dolerites described above, and should be grouped with them.

Specimen No. 837, of which No. 838 is a duplicate, appears in hand-specimen as a dark, fairly compact rock, somewhat pitted on the weathered surface, and showing occasional small phenocrysts of felspar. Under the microscope the rock is seen to be a typical fine-grained dolerite, wherein the pyroxene is predominant over the felspar, and resembling No. 732B in many respects. The felspar is present in two generations, the earlier being in thick tabular crystals, up to 3 mm. in length, and zoned ($Ab_{25}An_{75}$ to Ab_{45} An_{55}). Schiller inclusions are arranged along the pinacoidal cleavage-planes. The later plagioclase laths, averaging ·5 mm., have a composition about Ab_{35} An_{65} (Plate XXXIX, Fig. 2).

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[1] *Op. cit.* [2] Jour. & Proc. Roy. Soc. N.S.W., vol. xliii, 1911, p. 312.

The pyroxene is all monoclinic, pale-grey to pale purplish-grey, and is, in part at least, enstatite-augite; it is ophitic towards the felspar. Olivine is represented by abundant small individuals pseudomorphed by brown iddingsite (?), but a few aggregates are found representing original olivine nodules now changed to a pale-green strongly birefringent substance, suggestive of talc, and sometimes accompanied by carbonates. The marginal passage of this into a brown-coloured substance suggests that the material doubtfully referred to above as iddingsite may really result from the staining of this green talc-like mineral by iron (Plate XXXIX, Fig. 1).

The iron ore is skeletal ilmenite with a little magnetite; it is usually moulded on felspar but enclosed in pyroxene. A little pyrites has made its way along cracks in the felspar.

There is a small proportion of mesostasis in the rock, consisting of a greyish mineral that appears to be orthoclase, sometimes in parallel intergrowth with what is probably another felspar, and often crowded with magnetite granules and tiny apatite (?) needles. Very occasionally quartz fills the little interstices between the felspar laths.

The association of olivine and quartz in the same rock, though not unknown, is rather exceptional. Certainly the olivine is now completely altered, but the identity of the original mineral is beyond doubt. The quartz for the most part has the appearance of being primary, acting as an interstitial filling in which are embedded apatite needles and the ends of plagioclase prisms. A possible explanation is that the olivine grains and nodules represent early intratelluric crystallizations from the dolerite magma, which had sunk to the bottom of the magma-reservoir and were caught up in the still liquid portion of the magma at the time of its injection.

Specimen No. 456 is a medium-grained rock in which felspar (Ab_{35} An_{65}) and pyroxene are present in about equal proportions, and ilmenite of semi-skeletal habit is unusually abundant. The pyroxene is, in part at least, enstatite-augite, showing the salite striation at times and altering into chlorite enclosing tiny sphene granules, and into brownish uralite, the felspar showing sericitic and calcitic alteration. For the most part the pyroxene is moulded on the felspar, but occasionally the reverse relation holds. Quartz occurs interstitially in very small amount and never in pegmatitic intergrowth, and a very little apatite and biotite are also noticed. A feature of the rock is the presence of irregular interstitial patches of finer grain than the main body of the rock, consisting, as far as can be made out, largely of plagioclase, with subordinate augite largely altered to uralite. Ilmenite and magnetite are fairly plentiful in close association with augite; also elongated, tiny needles of what appear to be apatite, often with parallel arrangement. Little flakes of biotite are not uncommon, and there is a mesostasis consisting apparently of a felspar (? orthoclase) crowded with confused radiating aggregates of very tiny brown rods of some intermediate substance, possibly rutile[1]. The last phase of consolidation of the rock has been the introduction of pyrites, often along cracks in the felspar.

A very fine-grained type is represented by Specimens Nos. 449 and 457, which are really duplicates. The rock is hard, compact, and aphanitic, with a subconchoidal fracture in places, and showing tiny dendritic patches of pyrites on joint planes. It is holocrystalline, intergranular in fabric, and of notably uniform grainsize.

Felspar (acid labradorite) is arranged in little bundles of parallel laths up to ·3 mm. long, the bundles being oriented in all directions. The pyroxene is very plentiful in tiny light-green prisms and granules. It is predominantly if not solely monoclinic, but though the presence of enstatite-augite is suspected the small size prevents conclusive proof. Quartz is in fairly abundant interstitial patches, and an interstitial felspar of low R.I., probably orthoclase, also occurs, but never in intergrowth with quartz.

Magnetite is quite plentiful, and minute shreds of biotite and needles of apatite are fairly common. Infrequent vesicles are filled with chlorite. (Plate XXXIX, Fig. 3.)

A different type of rock is No. 459, which is close-grained and slightly vesicular in hand-specimen. It contains two generations of felspar prisms, both about $Ab_{35} An_{65}$, somewhat zoned, and often showing only Carlsbad twinning. Enstatite-augite, the dominant mineral, is moulded on the felspar, but typical ophitic fabric is not developed, the pyroxene being in small grains. Iron ores include both ilmenite and magnetite, and a little pyrites has been introduced subsequently to consolidation. Frequent patches of a fox-red pleochroic mineral (? iddingsite) may represent pseudomorphs after olivine, and a good deal of greenish and brownish chloritic material is present, sometimes forming cores to the felspar crystals. (Plate XXXIX, Fig. 4.) The abundant small interstitial spaces of the rock are filled with material of a light brownish-green colour, thickly charged with microlitic magnetite. This has a feeble polarization and may represent the devitrification of a glassy base.

All these rocks possess certain characteristics which link them with each other and with the quartz-dolerites, the most important being the presence of enstatite-augite and of quartz and orthoclase. Textural and mineralogical variations are such as might be expected in a differentiation series, and such indeed as have been described as resulting from the crystallization of quartz-dolerite magmas.

It is doubtful whether the rock labelled No. 208 should be grouped along with the dolerites just described. It is a dominantly felspathic rock, with prisms of labradorite averaging about 1·75 mm. in length, another felspar, probably orthoclase, being present in minor amount. Pyroxene is for the most part moulded on the plagioclase, and plays an interstitial role. This pyroxene is entirely monoclinic, and has a violet, or rather rose, colour, with distinct pleochroism, betokening the presence of titanium. Biotite is abundant, likewise ilmenite in semi-skeletal forms and rods. Apatite is scarce, and there are a few irregular patches of pyrites.

---

[1] *cf.* J. V. Lewis, Annual Report of State Geologist of New Jersey, 1907, p. 117.

The rock is considerably altered, the felspar being spangled with sericite flakes as well as with calcite and chlorite; in some places it appears to be altering to a zeolite.

Augite is much changed to a fibrous uralite, pleochroic as follows:—

X = Pale yellowish-green.
Y = Green.
Z = Bluish-green.

With $Y > Z > X$.

With the uralite change, there has been separation of iron oxide. Chlorite is another alteration product of the pyroxene. Biotite is irregularly bleached. Some of this mineral is probably primary, but much appears to be an alteration product of the augite. The section of an augite crystal is often covered over with tiny scraps of biotite, many of which are optically continuous and simulate the appearance of a graphic intergrowth with the augite. Some of the biotite and uralite contain pleochroic haloes surrounding tiny indeterminate colourless minerals. A number of irregular patches of yellow-green chlorite are seen, sometimes associated with little granules of carbonates and of secondary sphene; these may represent the ultimate alteration products of augite.

The rock may be termed an essexitic dolerite. (Plate XXXIX, Fig. 5.)

EXPLANATION OF PLATES.

All photographs have been taken in ordinary light unless when otherwise stated.

PLATE XXXVIII.

Fig. 1. Fine-grained quartz-dolerite from Horn Bluff (No. 732B). Note typical ophitic fabric. Patches of mesostasis are to be seen at the centre of the picture and elsewhere. x 27.

Fig. 2. Quartz-dolerite from Horn Bluff (No. 732A). The felspars, which act as a matrix, may be seen indenting the periphery of the pyroxene. The augite crystal on the left is cut parallel to (100), and shows indistinct basal striation. The mesostasis in which the felspars are set is well shown. x 17.

Fig. 3. Part of the pegmatitic quartz-dolerite (No. 733) from Horn Bluff. To the right of the vertical diameter is part of a long pyroxene individual twinned on (100) and showing serrated edges. The dark longitudinal band on it represents an alteration area in which the exceedingly fine basal striation is developed. The rectangular sections coming out horizontally from the top of this crystal are cross-sections of augite. At the right-hand side of the long pyroxene some granophyric mesostasis may be seen. Note the variation in the size of the plagioclase. x 17.

Fig. 4. Basic plagioclase, cut normal to (010) and (001), in graphic intergrowth with augite, in No. 733. Chlorite-stained granophyric mesostasis at top and sides. x 17.

Fig. 5. No. 733. Most of the field is occupied by mesostatic material, some in the position of extinction, consisting largely of felspar with rod-like or acicular development. To the left this is in contact with a twinned plagioclase crystal whose broad lamellæ are extinguished. Crossed nicols. x 59.

PLATE XXXIX.

Fig. 1. No. 837. Showing part of a nodule composed of olivine grains with some associated felspar and pyrites. The olivine has been altered to talc (?), the colour of which changes from very pale-green on the left to a greenish-brown on the right side of the nodule. x 17.

Fig. 2. No. 838. Showing part of a glomeroporphyritic aggregate of plagioclase. Crossed nicols. x 17.

Fig. 3. No. 449. Containing plagioclase, with granular augite and magnetite. A few small white patches represent interstitial quartz. x 27.

Fig. 4. No. 459. Showing on the left part of a glomeroporphyritic aggregate of plagioclase crystals whose central portions have been replaced by chlorite. x 27.

Fig. 5. Essexitic dolerite (No. 208). There may be seen augite, plagioclase, ilmenite (sometimes in rods) and chlorite (light irregular patches at top and right-hand side). x 17.

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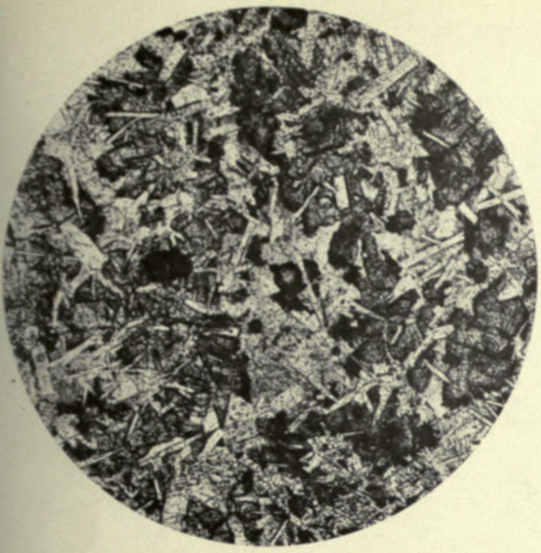

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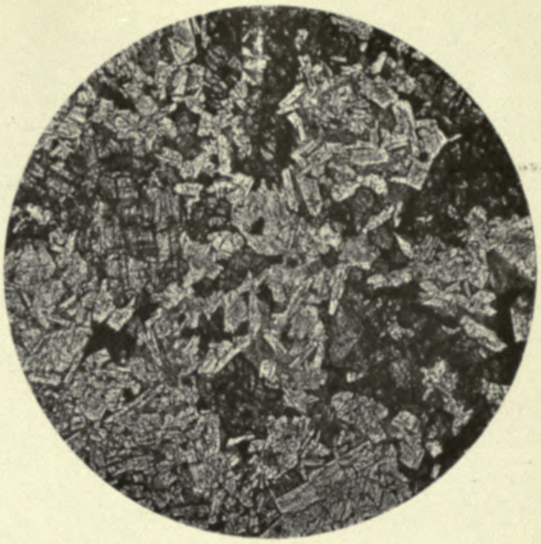

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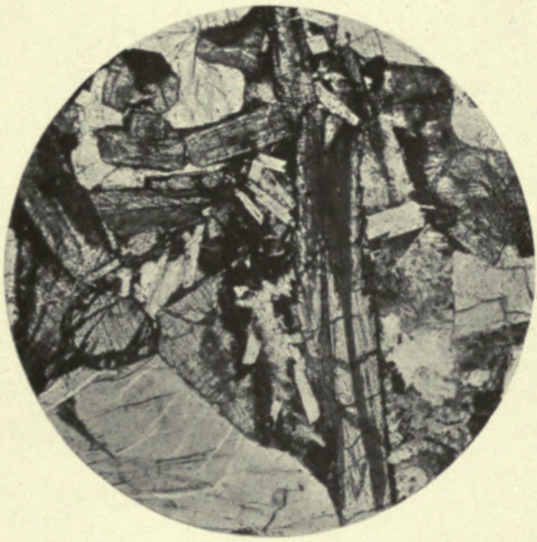

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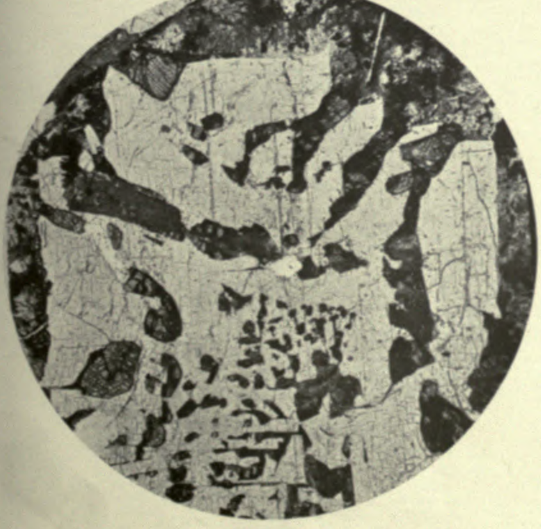

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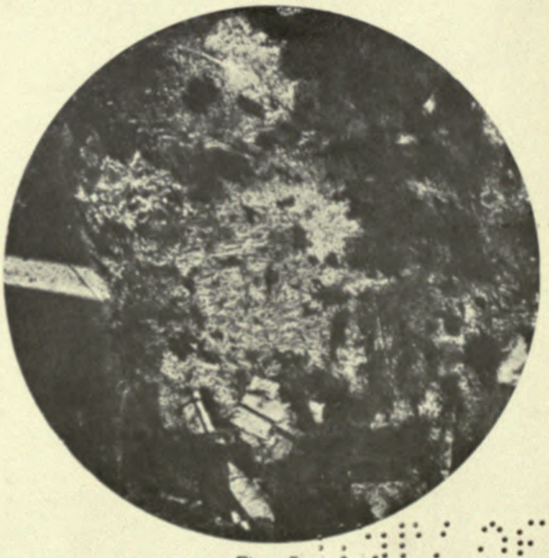

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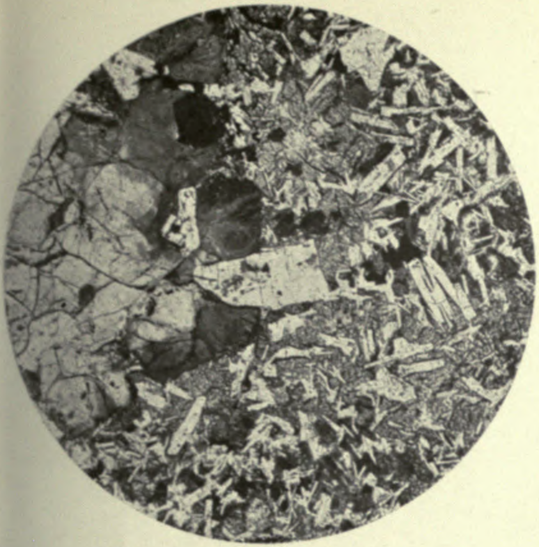

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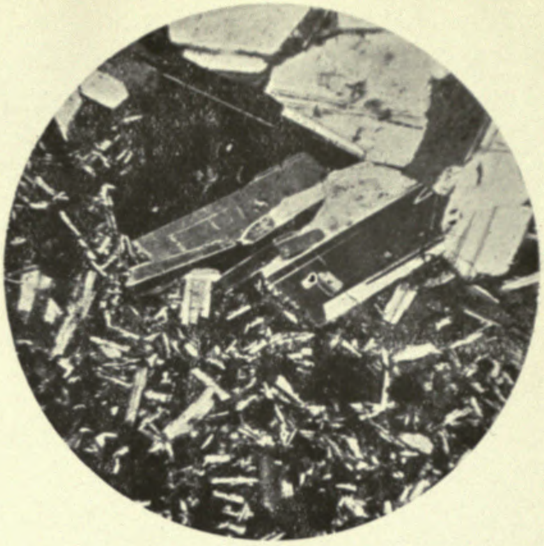

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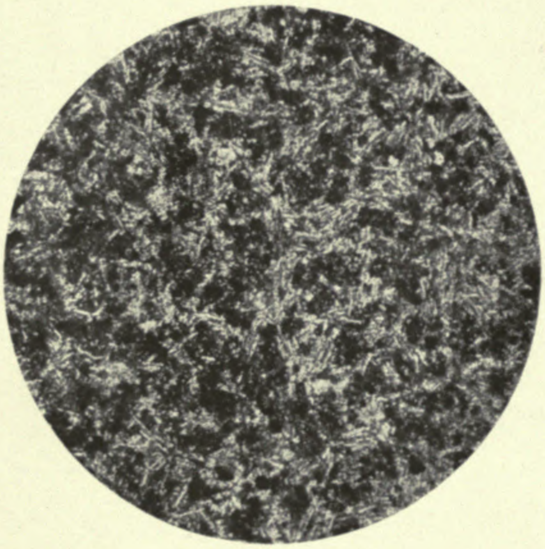

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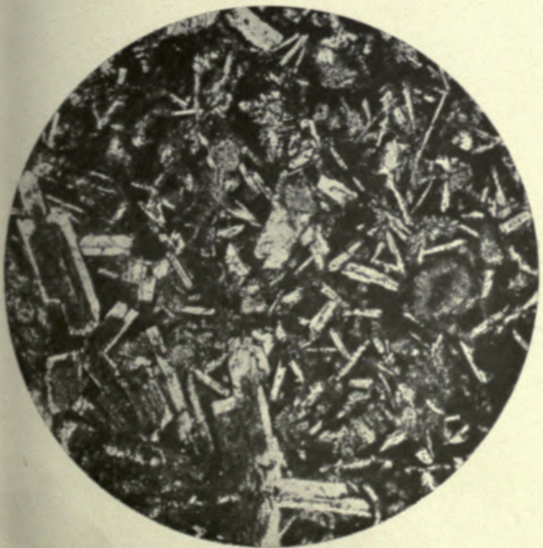

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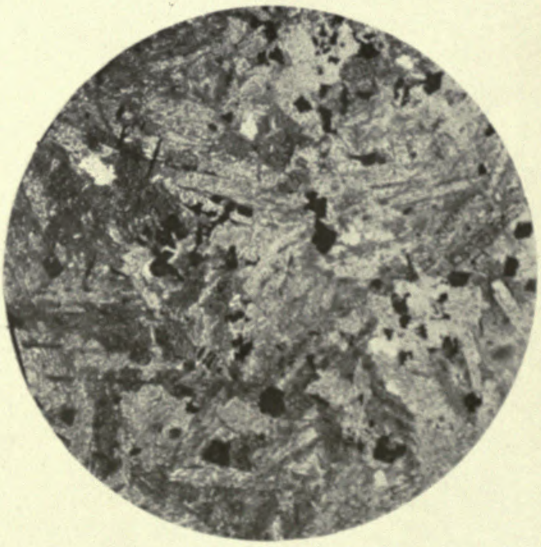

Fig. 5.

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1911-14.

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SCIENTIFIC REPORTS.

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AMPHIBOLITES AND RELATED ROCKS
FROM
THE MORAINES, CAPE DENISON, ADELIE LAND.

BY

F. L. STILLWELL, D.Sc.

WITH TWO PLATES.

PRICE: TWO SHILLINGS.

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No. 210, resembles the epidote-biotite-schist, No. 153, found *in situ*, except that biotite is replaced by chlorite.

Lawsonite-Chlorite-Amphibolite-schist.

No. 936, contains pyroxene and an excellent development of lawsonite.

*** The classification adopted is that proposed by U. Grubenmann in "Die Kristallinen Schiefer." Berlin, 1910.**

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4. Gabbro Schists and Gneisses 268

These differ from the other amphibolites in possessing an apparent coarse grain-size due to their derivation from coarsely-crystalline gabbros.

No. 915, a garnet-biotite-amphibolite.
No. 990, similar to No. 915 in which brown biotite is replaced by green chlorite.
No. 339, garnet-plagioclase-gabbro-gneiss.
No. 593, the gabbro structure is so well pronounced that the rock is similiar to a hornblende-gabbro
No. 367, with augen structure and the augen consist of aggregates of calcic andesine.
No. 969, with augen of saussurite.
No. 317, saussurite-gabbro-gneiss.
No. 728, saussurite-gabbro-gneiss with traces of the outlines of the original felspsr.
No. 861, saussurite-gabbro-gneiss with well-preserved form of original felspar.
No. 515, saussurite-gabbro-gneiss with branching veins of lawsonite and chloritisation of the hornblende.

III.—Group V.—Magnesium Silicate Gneisses 271

1. Kata Division 271

No. 527, pyroxene rock.
No. 963, hornblende-pyroxene rock.

2. Meso Division 271

No. 594, garnet-hornblende-schist.
No. 513, anthophyllite-schist, with abundant green hornblende and areas of talc.
No. 516, anthophyllite-schist with green hornblende and without areas of talc.
No. 109, anthophyllite-schist with plagioclase and without green hornblende.
No. 548, hornblende-fels, consisting wholly of hornblende.
No. 950, biotite-hornblende-schist.
No. 941, hornblende-fels, with granulitic hornblende developed from large platy hornblende.
No. 209, hornblende-schist with areas of talc.
No. 246, actinolite-schist.

3. Epi Division 274

No. 229, chlorite-hornblende-schist.
No. 888, hornblende-schist with large crystals of chlorite.
No. 229, chlorite-hornblende-schist.
No. 916, epidote-chlorite-schist.
No. 931, epidote-hornblende-schist.

IV.—Group III.—Plagioclase Gneisses 275

These rocks are more acid than the amphibolites and contain less hornblende or its equivalent.

1. Meso Division 275

Nos. 169, 170, hornblende-plagioclase-gneiss with schlieren of amphibolite and pyroxene.
No. 378, hornblende-felspar-gneiss, containing microcline as well as plagioclase.
No. 259, hornblende-plagioclase-gneiss, with subordinate biotite.
No. 240, Biotite-plagioclase-gneiss, with subordinate hornblende.
No. 956, Biotite-hornblende-felspar-gneiss. The hornblende resembles actionolite in form and colour, and biotite is more reddish than usual.
No. 51, hornblende-quartz-plagioclase-schist, with hornblende porphyroblasts embedded in a fine granulitic ground mass of quartz and felspar.
No. 924, hornblende-plagioclase-schist, resembles a porphyroide, but the base is a mass of densely-packed needles of hornblende.

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2. Epi Division 277

No. 257, epidote-felspar-schist.
No. 157, 522, epidote-felspar-schist with broader banding than No. 257, and containing a little quartz.
No. 726, epidote-felspar-schist with very broad bands of felspar and epidote.
No. 598, epidote-felspar rock with large porphyroblasts of microcline.
No. 954, chlorite-microcline-gneiss, belonging to the group of the alkali-felspar gneisses.
No. 590, epidote-felspar-schist with pink porphyroblasts or augen of felspar.
No. 910, epidote-felsar breccia, in which epidote occurs in a finely-granular form.
No. 592, epidote-felspar-gneiss, brecciated by veins of quartz and felspar and finely-granular epidote.
No. 591, epidote-felspar-gneiss in which the fine granular epidote occurs in wavy bands producing a helical structure.
No. 589, epidote-felspar-gneiss in which epidote is more abundant than No. 591.
No. 599, epidote-chlorite-schist containing more chlorite and less felspar than No. 589.
No. 255, an epidosite of Group IX which results when there is a deficiency of both chlorite and felspar.

V.—Description of Plates 280

I.—INTRODUCTION.

A GREAT variety of metamorphic rocks were collected from the moraines at Cape Denison, in Adelie Land, and the following notes give some account of the amphibolites and related rocks. Three specimens, which are specifically mentioned, are fragments of erratics found at Cape Hunter, nine miles west of Cape Denison. The basis of the grouping of these rocks is Grubenmann's chemical classification, with its zonal subdivisions, and this section includes Groups IV, V, and III, the Amphibolites and Eclogites, the Magnesium Silicate Gneisses, and the Plagioclase Gneisses. Each group is subdivided into three divisions (based on mineral composition and on structure) called the Kata, Meso, and Epi divisions. In the Kata division of these groups the pyroxene is in excess of the hornblende; in the Meso division the hornblende is in excess of the pyroxene; and in the Epi division there is a pronounced development of saussurite, lawsonite, epidote or chlorite, and also of mechanical structures. These groups are defined by their chemical composition, and the use of the classification is therefore restricted by the absence of complete chemical analyses. The chemical composition is, however, reflected in the mineral composition, from which the divisions of each group have been in most cases recognised.

The term *amphibolite* is used with the same meaning adopted in the memoir on the metamorphic rocks occurring *in situ* at Cape Denison.[1] It may be defined as a completely recrystallised rock of basic igneous chemical composition, whose mineral content is essentially hornblende and plagioclase. The latter mineral can be replaced wholly or partly by other minerals, such as zoisite, epidote, garnet, or scapolite. When the amphibolite possesses a strongly-foliated character it has been called an *amphibolite-schist*. In many cases the schistose structure is accentuated by the partial replacement of hornblende by biotite or chlorite, and the term *amphibolite-schist* becomes equivalent to the terms *biotite, chlorite or mica-amphibolite.*

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[1] "Metamorphic Rocks of Adelie Land." F. L. Stillwell. Scientific Reports, A.A.E., Vol. iii, pt. 1, pp. 24, 25.

This usage does not conform with the definition issued by the Joint Committee of the Geological Society of London and of the Mineralogical Society in the recent report on British Petrographic Nomenclature[1]. This Committee retain the term *amphibolite* for unfoliated or slightly-foliated metamorphic rocks of doubtful or other than igneous origin. It is composed essentially of hornblende and felspar, often containing various accessories, such as epidote and garnet. They distinguish *hornblende-schist* from amphibolite by the possession of a foliated texture.

On this basis completely recrystallised rocks, which consist of hornblende and felspar, and which possess a slightly-foliated structure, are excluded from the family of amphibolites when they are derived from igneous rocks. It would appear to be the intention of the Committee to include such cases among the *epidiorites* which are defined as unfoliated basic igneous rocks in which the augite is completely altered to hornblende. They seem to have overlooked the fact that two types of altered basic hornblende rocks, occurring in the form of a dyke or sill, can be recognised,—(1) those in which the ferro-magnesian has suffered recrystallisation, and (2) those in which both the ferro-magnesian and felspar have suffered recrystallisation. These two types may be encountered in one area, as at Broken Hill (New South Wales), where they are readily distinguishable from one another in the field, in the hand specimen and under the microscope. The term *epidiorite* covers the first type, and it is clearly undesirable to extend it to the second type, which is identical with *amphibolite.*

A typical amphibolite will contain 60 to 70 per cent. of hornblende and about 25 to 30 per cent. of felspar. Other metamorphic rocks occur which contain nearly all hornblende and practically no felspar, and it is necessary for precise description to distinguish these from the typical amphibolite. It is also desirable to distinguish between the foliated amphibolite and the hornblende schist with felspar in excess of the hornblende. These metamorphic types, in which hornblende is an important constituent, may be tabulated as follows :—

Mineral composition.	With massive structure.	With foliated structure.
Mainly hornblende	Hornblende fels	Amphibole or hornblende-schist.
Hornblende in excess of felspar...	Amphibolite	Amphibolite-schist or mica-amphibolite
Felspar in excess of hornblende	Hornblende-plagioclase-gneiss	Hornblende-plagioclase-schist.

The massive types pass by gradual transitions into the foliated types. It is obviously difficult to restrict the term *hornblende-schist* to foliated amphibolites, as recommended by the Joint Committee. It is more logical to use the term for the pure amphibole types as has been done by Grubenmann[2]. The term *amphibole-schist* includes rocks which contain more than one variety of amphibole, but those which contain anthophyllite are referred to as anthophyllite schists in the following pages.

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[1] "Report on British Petrographic Nomenclature." Min. Mag., Vol. xix, No. 92, pp. 137-147, 1921.

[2] "Die Kristallinen Schiefer." U. Grubenmann. Berlin, 1910, p. 216.

II.—Group IV.—THE AMPHIBOLITES AND ECLOGITES.

At Cape Denison the variety of types occurring *in situ* is considerably increased by a study of specimens collected from the moraines. The main occurrences *in situ* consist essentially of felspar and hornblende, with or without biotite. They have been looked upon as basic igneous dykes which have recrystallised under conditions varying from those of Grubenmann's Meso zone to those of the Epi zone. The moraine types include representatives of the Epi, Meso, and Kata divisions, and some are similar to members of the Cape Gray series, occurring 25 miles to the east.

Kata Division.

The distinguishing feature of the Kata division of this group is the abundance of pyroxene. A representative is specimen No. 937, a hornblende-plagioclase-pyroxene-gneiss, which possesses similar features to the plagioclase-pyroxene-gneiss, No. 773, from Cape Gray, and to the plagioclase-pyroxene-gneiss, No. 935, from Stillwell Island[1]. Like Nos. 773 and 935, it possesses large relic crystals of augite, which have recrystallised partly as clear granular pyroxene and partly as hornblende. Like No. 773, it possesses traces of the original felspar laths of the original dolerite. Its felspar is a clear basic labradorite, appearing partly as lath-shaped crystals, but mostly as coarse granular crystals of the same average grain size as the hornblende and pyroxene. It contains a few flakes of biotite and a few disseminated and minute grains of ilmenite.

Related to this type are two erratics (Nos. 962 and 967), from Cape Hunter, 9 miles west of Cape Denison. These are hornblende-plagioclase-pyroxene-gneisses, in which the pyroxene is in excess of the hornblende. Garnet is absent, and the pyroxene includes both augite and hypersthene. Basic felspar is an important constituent, and, in addition, the rocks carry a little biotite and accessory apatite and ilmenite.

Numerous pink garnets are present in No. 595, a type closely related to the garnet-plagioclase-pyroxene-gneiss, No. 935, from Stillwell Island. Some of the garnets tend to form a zone between the pyroxene aggregates and the plagioclase. The felspar occurs as large crystals of basic labradorite and as granulitic aggregates of a less calcic felspar, probably andesine. Some of the larger crystals contain cloudy alteration products. Quartz is present, and has probably developed with the formation of garnet by the interaction of felspar and pyroxene. There is a considerable amount of hornblende, derived from the alteration of the pyroxene, which is associated with numerous large grains of ilmenite, probably derived from the same source. This garnet-bearing type is related to the eclogite family, but the clear omphacite of the typical eclogite is absent.

Specimen No. 227 is a dark, glistening schistose rock, showing abundant pink garnet and black biotite in the hand specimen. It also possesses a thin lenticle of segregated quartz along the schistosity, which may have developed with the formation of the garnet. In section, the rock has a coarsely-crystalline schistose structure, and the brown biotite is the most abundant mineral along some of the schistose bands. The plagioclase is mostly andesine, and varies towards labradorite. It is mostly clear, and only occasional grains show alteration. Pyroxene occurs in large crystals along one schistose band, and in smaller crystals in other parts of the rock. It includes hypersthene, augite, and fibrous diallage, from which ilmenite has separated out. Only occasional crystals of green hornblende are present. Garnet occurs in large pink crystals up to 6 mm. in diameter, with numerous inclusions, and also in small idioblastic crystals. A little quartz is present, and there are large accessory crystals of apatite and zircon. The rock may be called a garnet-biotite-plagioclase-gneiss. It differs from members of the eclogite family in the large development of biotite in place of pyroxene.

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[1] Op. cit., pp. 169, 172.

MESO DIVISION.

The conditions of the Meso zone metamorphism are considered to become more important in the formation of the augite-amphibolites. Several examples, including Nos. 380, 351, and 212, exist in the collection; and the percentage of hornblende in these is in large excess of the percentage of pyroxene. They resemble the pyroxene amphibolites described from the Cape Pigeon Rocks.[1] Of these specimens No. 212 is remarkable in possessing large, dark-green porphyroblasts of a very calcic felspar. Some of these crystals are over an inch in width, and possess well-defined crystal boundaries. The texture of the rock is massive, and the structure is typically granoblastic and porphyroblastic. The mineral composition of the rock, excluding the porphyroblasts and the accessory minerals apatite and ilmenite, is :—

Felspar	31·4 per cent.
Hornblende	64·8 ,,
Pyroxene	3·8 ,,

The proportion of felspar to the ferromagnesian in this case is practically the same as in the Cape Denison amphibolites. The felspar is quite clear and unaltered. Most grains show lamellar twinning and are highly calcic. The hornblende is green and fresh, without the tinge of blue colour noticeable in many of the amphibolites with Epi zone features. The pyroxene includes both augite and hypersthene.

The porphyroblasts possess crystal outlines, and, like the felspar in the base, are perfectly clear and free from traces of decomposition. They show complex twinning, and, in addition to simple twinning, there are at least two sets of lamellar twinning. They contain small inclusions of pyroxene and hornblende. The pyroxene inclusions tend to occur in rounded grains, while the hornblende inclusions develop their crystalline form against the plagiolcase. The inclusions in many places show a linear arrangement along cleavage lines and twinning planes. The presence of these inclusions and the fresh character of the plagioclase in the base of the rock indicate that these large crystals have developed during the recrystallisation, under the conditions of the formation of the amphibolite. The absence of any relic structure is important negative evidence that these porphyroblasts were not phenocrysts in the original igneous rock.

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[1] Op. cit., p. 180.

A sample of the porphyroblastic felspar was separated and freed as far as possible from the ferromagnesian inclusions by hand picking and by the use of heavy solutions. The sample was then analysed by Mr. J. C. Watson in the Victorian Geological Survey Laboratory.

SiO_2	45·92
Al_2O_3	35·34
Fe_2O_3	1·05
MgO	str. tr.
CaO	16·39
Na_2O	1·70
K_2O	·20
H_2O	·33
H_2O	·00
	100·93

This analysis demonstrates the highly calcic nature of the porphyroblast which approximates to Ab_1An_6.

Specimen No. 547 is a remarkable quartz-pyroxene-amphibolite. It is distinguished as one of the very few specimens occurring on the moraine with a weathered crust. It is a heavy basic rock, and a rough determination of its specific gravity gave 3·25. It is rather coarse-grained, and possesses a slight schistose character. In section it is found to be similar in structure and character to the other specimens of pyroxene-amphibolites, except that the felspar is completely replaced by quartz. The amount of quartz is approximately the same as the amount of felspar in the typical amphibolites. No garnet is present in the section, but grains of ilmenite and pyrite are unusually abundant, and partly account for the high specific gravity.

The Meso division of the amphibolites is more typically represented by a number of amphibolites and biotite-amphibolites which are similar to some of the occurrences *in situ* at Cape Denison. In the typical examples the plagioclase is clear and often untwinned, and in Nos. 946 and 959 the hornblende crystals contain numerous clear inclusions of felspar and quartz, producing a " sieve " structure. In another case, No. 865, there are numerous porphyroblasts of felspar, which average about 5 mm. in width. This specimen was part of a large erratic in which the porphyroblasts were arranged in a linear manner and parallel with the schistosity—an occurrence in strong contrast with the scattered occurrences of metamorphic xenoliths in the amphibolite *in situ* at Cape Denison[1]. Apart from the porphyroblastic character the rock is a typical amphibolite, with dominating hornblende and very little brown biotite. The felspar is clear andesine with indefinite and intermittent twinning.

A schistose variety is represented by No. 597, in which the light-coloured constituents are sufficient to produce a greyish colour in contrast to the black colour of the normal amphibolite. It is a biotite-amphibolite-schist, carrying lawsonite, epidote, and coarse crystals of apatite. The epidote and lawsonite are interlaminated with biotite, and the development of these minerals indicate an approach to the Epi division of this group.

EPI DIVISION.

Specimen No. 985 is a jet black schistose chlorite-amphibolite, similar in most respects to the preceding variety, No. 597. The biotite of No. 597 has been mostly converted into chlorite in No. 985, and most of its felspar has been saussuritised. These changes are considered to be Epi features, superimposed upon a typical amphibolite. Large vein-like segregations of saussurite are present in the hand specimen of No. 985.

Another chlorite-amphibolite is specimen No. 520. Biotite is completely replaced by chlorite, and the alteration is accompanied by the separation of a little quartz. An interesting feature in this case is the separation of the blue glaucophane constituent from the complex molecule in a manner similar to the schiller inclusions that are sometimes found in hypersthene. The result is a mottled green and blue crystal of hornblende (Pl. XL. fig. 1). Apatite and ilmenite are abundant minor constituents, and most of the felspar is cloudy and saussuritised except for small areas of clear albite.

The same mottling of blue and green hornblende is developed in a lesser degree in the amphibolite No. 965. This specimen possesses a pronounced " sieve " structure, in which the hornblende is highly perforated with colourless inclusions. The plagioclase is cloudy. Some of it possesses prominent diablastic structure, representing one stage of its development, but most of it forms a fine granulitic aggregate of acid plagioclase. Crystals of apatite and ilmenite are large and unusually abundant. A little chlorite is present, derived from biotite, and pyrite is also present.

Another variety of chlorite-amphibolite is No. 247. This specimen is a schistose rock, in which abundant lenticles or porphyroblasts of felspar are set in a dark matrix of hornblende, mica, and felspar. The base of the rock is similar to the biotite-amphibolites, except that biotite is replaced by chlorite. In this and the preceding examples the chloritisation does not extend to the hornblende. Quartz is present showing cataclasis, and, together with the abundant felspar, indicates a gradation towards the more acid group of the plagioclase gneisses. Some of the felspar lenticles consist of large saussuritised plagioclase, partly surrounded by clear, recrystallised felspar. Others consist of granoblastic masses of andesine felspar, with a little quartz.

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[1] Op. cit., p. 48.

Scattered grains of epidote, chlorite, and muscovite occur in the felspar areas. In this case, the features of the Epi division include the presence of epidote and the cataclastic structures, in addition to the presence of saussurite and chlorite.

Specimen No. 828 is a similar porphyroblastic chlorite-amphibolite, but the cataclasis and mortar structure are much more pronounced. The margins of the hornblende crystals have been crushed and converted into chloritic selvages. The porphyroblasts of felspar are elongated along the schistose planes, and are surrounded by chlorite and finely-granulitic quartz and felspar. This rock also contains occasional large crystals of allanite.

Specimen No. 961 is an Epi-amphibolite, in which the hornblende crystals display a remarkable mortar structure. It is a highly schistose rock, containing a a larger percentage of hornblende than the typical amphibolite. The fracturing and grinding of the fragments of hornblende have produced zones and films of green chlorite around islands of unaltered hornblende. A blunt hornblende crystal often assumes a lenticular shape where the chloritic brash is drawn out along the schistosity. The clear mineral is an acid plagioclase, frequently drawn out into lenticular shapes along the schistosity. Some crystals show a mortar structure, while others have been reduced to finely-pulverised aggregates.

Specimen No. 233 is a chlorite-amphibolite, in which the alteration of hornblende into chlorite has been extensive. It contains large pale green to colourless crystals of hornblende, which are all partly converted into chlorite. The greater proportion of the chlorite, which is the most abundant mineral in the rock, has been formed in this way. A subordinate quantity of chlorite appears to be pseudomorphous after biotite. The felspar is cloudy, and occurs in granular crystals. Though mostly untwinned, it is probably an acid plagioclase. In a vein that traverses the section, it has recrystallised as clear albite. Ilmenite, granular sphene, and apatite are distributed freely through the rock. Epidote is a minor constituent, except in the neighbourhood of the vein, where it is associated with chlorite and clear albite.

Specimen No. 210 is an interesting relative of the epidote-biotite-schist, No. 153, which occurs as an altered dyke rock at Cape Denison[1]. Its structure is more massive and less schistose than No. 153. The biotite of No. 153 is replaced by a green pleochroic chlorite, and epidote crystals are more numerous than in No. 153. The clear felspar is an acid plagioclase, and no basic felspar is present. Sphene and magnetite (or ilmenite) are important minor constituents, and are associated together in the same manner as in the typical amphibolites. Apatite is an accessory mineral, and there are occasional grains of calcite. The amount of felspar appears to be less in this rock than in No. 153, tending to make this specimen a typical member of the family of epidote-chlorite-schists.

An interesting specimen is the lawsonite-chlorite-schist, No. 936. It is one of the few specimens from this region which shows surface weathering, being covered with a brown iron-stained skin. A brown colour also appears on the fractured surface,

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[1] Op cit., p. 30.

and is due to the presence of the golden-brown mica on the schistose surface, such as is characteristic of the lawsonite-amphibolites at Cape Denison. The ferromagnesian constituents include pyroxene, hornblende, biotite, and chlorite. The pyroxene, which constitutes 5 per cent. of the rock, has the granular character and pale colour common in the plagioclase-pyroxene-gneisses. In some cases it passes over directly into chlorite, but its alteration to green hornblende is more common. Green hornblende forms about 14 per cent. of the rock, and the remaining four-fifths of the rock consists chiefly of biotite with lawsonite and chlorite, saussuritised felspar, and clear acid plagioclase. Biotite possesses the curious reddish-brown colour previously seen in the lawsonite amphibolite (No. 635), occurring *in situ* at Cape Denison, and shows various stages of decolouration in its alteration to chlorite. Colourless lobate lenticles of lawsonite are interlaminated with both biotite and chlorite. Lawsonite is also well developed in the chloritic and saussuritised areas. The saussuritisation of the plagioclase has been fairly complete. The albite molecules have reappeared as clear acid plagioclase, while the anorthite molecules have combined with water and produced lawsonite and granular epidote. Fibrous chlorite is also abundant among these aggregates, and there is a little quartz and white mica. Sphene, ilmenite, and pyrite are important accessory minerals, and isolated grains of allanite and apatite are present.

Lawsonite, chlorite, and epidote indicate the relationship of this rock to the Epi division. The presence of pyroxene indicates that the rock was previously subjected to Kata zone metamorphism, being probably a plagioclase-pyroxene-gneiss. These conditions are superseded by the hornblende-producing conditions of the Meso zone, which were finally superseded again by the Epi zone conditions of recrystallisation which now characterise the specimen.

Gabbro Schists and Gneisses.

In addition to the typical amphibolites, the collection contains a number of handsome hornblendic rocks of apparent coarse grain. They possess the same mineralogical variety and composition as the amphibolites. In many cases they possess the same average grain size, but the minerals are grouped in clusters, so that the hand specimen assumes a mottled black-and-white character, with the appearance of a coarse-grained rock. In these cases they are amphibolites, with the glomeroplasmatic structure described by Lœwinson-Lessing, and Holmes.[1] The mineral grouping indicates either (1) that each cluster has been derived from an original crystal unit, or (2) that each cluster is a minute metamorphic differentiation. The average regularity of the areas throughout the hand specimens renders the first explanation the more probable. In some cases this explanation is confirmed where the white areas have retained the form of felspar crystals, and the rocks are metamorphic representatives of gabbros. Some of the types may have been placed in order among the amphibolites, but the "relic" gabbro structure of the hand specimens has favoured their consideration under the heading of gabbro schists and gneisses.

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[1] Trav. Soc. Nat. St. Petersb., vol. xxv (1900), p. 208; A. Holmes, Q.T.G.S. lxxiv, 1918, p. 55

Specimen No. 915 is an example of a garnet-biotite-amphibolite with glomeroplasmatic structure, and is similar to No. 50 (Pl. XLI, fig. 1). In section, it is found that the dark areas of hornblende crystals consist of small lenticular clusters, together with biotite and ilmenite. The white areas are granoblastic aggregates of basic plagioclase. A similar specimen is No. 990, in which the brown biotite is replaced by green chlorite, and more of the felspar is saussuritised.

No. 339 is a garnet-bearing gabbro-gneiss (Pl. XLI, fig. 2). It possesses a coarse gneissic structure, and has a mottled appearance. The black areas consist of aggregates of hornblende and augite, or garnet and biotite, but the four minerals are contained in some aggregates. The white areas, which are slightly discoloured by weathering, consist of aggregates of labradorite, partly saussuritised, and a little quartz. The biotite aggregates contain a little lawsonite, and their rounded form suggests their derivation from garnet[1]. The suggestion is supported by the presence of quartz, which can be formed with the change from garnet to biotite. The hornblende has been derived from augite, while the granular form of the metamorphic pyroxene suggests its derivation from large platy pyroxene crystals. Ilmenite and apatite are accessory minerals. The microscopical features are similar to those of the hornblende-pyroxene-gneisses, with the addition of the glomeroplasmatic structure.

A specimen in which the gabbro structure is very prominent is No. 593, whose character would be well described as a hornblende-gabbro. It is a coarse, handsome rock, containing some large crystals of labradorite, though consisting for the most part of coarse hornblende and felspar. Occasional crystals of green augite are associated with the hornblende, and a few fragments of garnet are found near plates of biotite. In thin section the labradorite has a tendency to idiomorphic outlines—a contrast to the granoblastic aggregates of many metamorphic rocks. The twin lamellæ of the labradorite are very broad and much more abundant than in previous types, but there is a small amount of untwinned sodic felspar. The hornblende forms large crystals, but in other respects is similar to the smaller crystals in the amphibolites. Augite is present, and in one case forms the nucleus of a large hornblende crystal. Large crystals of ilmenite, with sphene rims, accessory apatite, and zircon are present. While the nature of the rock is understood by the name "hornblende-gabbro," the rock possesses metamorphic traits in the presence of relic garnet, of secondary felspar, saussuritised felspar, and the characteristic relation of sphene and ilmenite.

In specimen No. 367 some of the felspar areas are 2 cm. wide, and the rock has the appearance of an augen gneiss. The section shows that the felspars have recrystallised as granoblastic aggregates of calcic andesine, fairly free from saussurite. Coarse crystals of epidote are present. Some of the biotite is replaced by chlorite and is intergrown with lawsonite. The Epi zone features are, however, subordinate in this example, and the rock may be called a plagioclase-gabbro-gneiss. The plagioclase is thoroughly saussuritised in a somewhat similar specimen, No. 969 (Pl. XLI, fig. 3).

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[1] Op. cit., p. 157.

Specimen No. 317 is a coarse-grained rock, with a mottled black-and-white appearance, due to glomeroplasmatic areas of hornblende and felspar of average width of 3 to 4 mm. Each dark hornblende mass resolves itself on examination into clusters of small crystals, associated with crystals of chlorite, ilmenite, and apatite. This ilmenite may have been discharged from the original pyroxene in the manner recorded in the garnet-plagioclase-pyroxene-gneiss, No. 935, from Stillwell Island[1]. Biotite is replaced by chlorite and epidote. In the white areas are large saussuritised felspars, in which sericite, white mica, epidote, chlorite, and zoisite are found, in addition to clear albite. There are also areas of clear labradorite, and a few scattered fragments of garnet. The rock may be distinguished as a saussurite-gabbro-gneiss.

Specimen No. 728 is another variety of saussurite-gabbro-gneiss. Its felspar is completely saussuritised, and there is a little garnet and a small development of secondary quartz in the hornblende, probably associated with the development of epidote and chlorite. The specimen is not schistose, and the outline of the original felspar crystals is discernible in the hand specimen, averaging about 6–7 mm. long and 2–3 mm. wide. The form of the felspar is even better preserved in No. 861, where it is sufficiently obvious to suggest that the hand specimen is a hornblende-felspar-porphyry. There is, however, complete saussuritisation of the felspar, while the biotite and some of the hornblende is converted into epidote and chlorite. Scattered garnets occur around the fringe of some of the hornblende clusters, and are suggestive of the garnet roms around the pyroxene in the garnet-pyroxene-gneisses of Stillwell Island.

The conversion of hornblende into chlorite is further advanced in specimen No. 515, another saussurite-gabbro-gneiss. The chloritisation of the hornblende proceeds from the edges and cleavage cracks. The section is crossed by branching veins of lawsonite (Pl. XL, fig. 2), which have developed during the saussuritisation of the felspar. These veins cross hornblende as well as felspar areas. Zoisite occurs with the epidote in the altered areas. There are, however, considerable areas of unaltered basic felspar.

Apart from the gabbro gneisses and the amphibolites that have been described, there are a number of coarse-grained hornblendic rocks. With the segregation of the lighter-coloured constituents, these rocks become representatives of the hornblende-plagioclase-gneisses of Group III. With the segregation of the darker constituents, they grade towards the hornblende schists of Group V. Specimen No. 721 (Pl. XLI, fig. 4) illustrates a segregation assuming the form of a vein. The vein contains large crystals of hornblende, some of which are 3 cm. long, together with felspar and a little quartz. A similar vein occurs on the edge of another specimen, No. 25, in which there is a noticeable increase in grain size of the amphibolite as it approaches the edge of the vein.

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[1] Op. cit., p. 174.

III.—Group V.—MAGNESIUM SILICATE GNEISSES.

As the percentage of felspar decreases the members of the Amphibolite Group grade into the rocks of Group V, the magnesium silicate gneisses.

Kata Division.

Assigned to the Kata division of Group V is Specimen No. 527, an apple-green rock, consisting essentially of granular green pyroxene. It consists, in section, of a granulitic mass of clear pyroxene, resembling omphacite, with a subordinate amount of very pale green to colourless hornblende, together with a little interstitial quartz. Garnet is absent; and, otherwise, the rock would be classed as an eclogite in Group IV. The development of hornblende is irregular, and sometimes is accompanied by a little biotite. Portions of the specimen possess a distinctly dark-green shade, due to an increased amount of hornblende. One portion of the specimen possesses a noticeable percentage of red felspar, indicating the relationship with the amphibolite group. This particular specimen is traversed by a vein of quartz and plagioclase, 2 cm. wide, in which the quartz is mostly confined to the centre of the vein, and the plagioclase to the walls of the vein.

In Specimen No. 963 the hornblende is much more important, and the hand specimen possesses a corresponding dark colour. This specimen was obtained from an erratic on Cape Hunter. The main constituent of the rock is pyroxene, including both augite and hypersthene. Some of the crystals are clear and granular, and others are fibrous. All show more or less alteration to hornblende. There is a small development of brown biotite accompanying the hornblende, subordinate plagioclase, and scattered grains of ilmenite and pyrite.

These rocks are unfoliated, and therefore possess resemblances to the ultra basic igneous rock "pyroxenite"; but the pyroxene possesses the distinctive character of the granular pyroxene of metamorphic origin commonly observed in the Cape Gray series of altered basic dyke rocks.

Meso Division.

As hornblende becomes the essential constituent the types are grouped in the Meso division of Group V. Among these is Specimen No. 594, a garnet-hornblende-schist. It is a coarse-grained, dark-green rock, which consists of green hornblende and scattered pink garnets. In addition, there is a little interstitial felspar, as well as scattered grains of ilmenite and apatite.

Specimen No. 513 is a heavy, dark-green, slightly schistose rock, consisting essentially of amphibole, with scattered specks of pyrite visible in the hand specimen. In thin section there are large talcose areas produced by the decomposition of some pre-existing crystals. These contain numerous inclusions of magnetite and amphibole. The magnetite appears to have been a separation product, accompanying the formation of the talc. It is distributed as fine particles along traces of former cleavage planes, and along a system of cracks more or less at right angles to the cleavage. In many places these particles have coalesced to form irregularly-shaped inclusions of magnetite. The arrangement of the discharge of magnetite suggests that the original crystals were olivine, though the nature of some of the included amphibole indicates the possibility of pre-existing pyroxene, partly altered to hornblende before the curious alteration to talc. The amphibole is the most abundant mineral, and includes green hornblende and anthophyllite. The latter has developed in long prismatic crystals, which possess faint pleochroism from colourless to very light brown. The cross sections show the usual hornblende cleavage and outline, and the prismatic sections possess straight extinction. Sometimes there is a green core of hornblende, with a colourless border zone of anthophyllite. Sometimes the hornblende is decolourised, and there appears to be a gradation from hornblende to anthophyllite. In addition to these minerals, the rock contains a minor amount of biotite, with pleochroism from a pale-straw brown to a bright green, and of magnetite with accessory grains of pyrite, apatite and quartz. The rock is an anthophyllite-schist, on which has been superimposed some of the features of the Epi division. These features include the development of talc, the bent and crushed appearance of some of the biotite crystals, and the occasional fracturing and mortar structure in the amphibole.

Specimen No. 516 is another representative of the anthophyllite-schists, and, as in No. 513, there are only occasional grains of felspar. It is a dark-green schistose rock, showing a brownish tinge on the weathered surface, due to the slight oxidation of anthophyllite. In thin section, the green hornblende is the most important mineral, and the colourless to light-brown anthophyllite is intergrown with it. The talcose areas of the preceding specimen are absent, but some of the anthophyllite crystals show decomposition around their edges and cleavages to a talcose material. Brown biotite is much more abundant than in No. 513, and helps to produce the schistose structure. Accessory grains of apatite, ilmenite, pyrite and quartz are present.

Another representative of the anthophyllite-schists is Specimen No. 109, in which the green hornblende is absent. This specimen is a light-brown rock, in which the prisms of anthophyllite are arranged with their long axes in the plane of schistosity. Some of these crystals are over 2cm. long, and they lie in all positions in this plane. Plagioclase can be observed in the hand specimen in a proportion which makes the inclusion of this specimen in this group doubtful. In section the anthophyllite is slightly pleochroic from colourless to pale brown, showing the well-developed cleavage and outline of the amphiboles. The plagioclase is labradorite, and there are odd flakes of biotite and a few grains of magnetite (or ilmenite). The rock could possibly be placed in the group of the amphibolites.

A typical hornblende-fels is No. 548, a black, heavy, massive rock. It is fairly coarse-grained, and in the hand specimen appears to consist wholly of hornblende. In section, it is composed chiefly of fresh green hornblende, containing a few inclusions of rounded quartz blebs. Quartz is the more important minor constituent, and there are, in addition, accessory flakes of biotite, grains of felspar, calcite, apatite, and ilmenite.

Specimen No. 950 is a biotite-hornblende-schist, which is closely related to the biotite-amphibolites. It contains felspar and a little quartz, but in less amount than in the typical amphibolites. The brown biotite is abundant, but not uniformly distributed through the rock. It forms clusters, in which some of the micaceous laminæ are bent and twisted. Occasional grains of epidote are associated with the biotite. Green hornblende is the most abundant constituent, and both the hornblende and biotite possess pleochroic haloes, which surround minute inclusions.

A curious hornblende-fels is No. 941. It is a dark-green, massive rock with a porphyroblastic appearance, due to platy crystals of hornblende, which are set in a fine matrix. The examination reveals the large hornblendes as relic crystals which have for the most part broken down into granulitic aggregates of a similar pale-green hornblende (Pl. XL, fig. 3). The latter forms the bulk of the thin section. A little colourless chlorite and a little brown biotite are mixed with the granulitic hornblende. Embedded in these aggregates are a few long, slender prisms with ragged terminations, which are feebly pleochroic from colourless to pale green. Some show lamellar twinning, and they possess straight extinction with yellow and grey polarisation colours of the first order. They show cleavage, and appear to be a form of orthorhombic amphibole. The remaining constituents are ilmenite dust, and grains of pyrite and apatite. It would appear as if the original platy hornblende had been chloritised and the reaction had then been reversed, reproducing the fine granulitic hornblende from the chlorite.

Another dense hornblende-schist is No. 209, in which a subordinate amount of biotite, for the most part converted into chlorite, is associated with the pale bluish green, granular hornblende. It contains large talcose areas, similar to those in No. 513, produced by the decomposition of pre-existing olivine or pyroxene. These areas form about half of the section, and contain magnetite in a similar manner. They are studded with inclusions of hornblende and chlorite, but there is no trace of the original mineral.

The family of actinolite-schists is represented by specimen No. 246, which displays in the hand specimen a bright green mass of acicular crystals. Its appearance forms a distinct contrast to that of the dark greenish black hornblende-schists. In thin section it consists almost entirely of a mass of long thin actinolite prisms, which are pale green to colourless. A few flakes of biotite and a few scattered grains of ilmenite are the only other minerals present.

EPI DIVISION.

A larger development of chlorite occurs in specimen No. 229, which may be called a chlorite-hornblende-schist. The formation of chlorite has been accompanied by the development of a little epidote, and the separation of a little quartz. In places the ends of the hornblende crystals are frayed out into needles embedded in quartz. Some of the hornblende crystals show the effects of crushing, with an alteration toward chlorite. Ilmenite is disseminated through the section, and there are occasional grains of untwinned felspar. The marked development of chlorite is a feature associated with the Epi division of this group, in which this rock has been included.

Another specimen of hornblende-schist, No. 888, contains a curious plate of chlorite, which is composed of layers of chlorite. In each layer the micaceous laminæ of chlorite are arranged more or less at right angles to the trend of the layer; but the laminæ in adjoining layers are set at varying angles in one another. Both chlorite and hornblende in this specimen possess a very pale green colour, being nearly colourless.

A specimen that can be placed in this division is No. 916, a dense, dark green pebble bearing glacial striæ. It is a close relative of the epidote-chlorite-schists of Group IV, but it is distinguished by its very subordinate amount of clear felspar. It consists chiefly of epidote and chlorite. The iron, which has been discharged during the conversion of biotite and hornblende into epidote and chlorite, is disseminated throughout as numerous small particles of ilmenite. A little zoisite is associated with the epidote. Sphene and apatite are not observed, but white mica is a minor constituent. The rock is an epidote-chlorite-schist; and, since chlorite is the more important constituent, it is included in the family of chlorite schists. If epidote had been more important, the rock would be related to the epidosites of the Epi division of Group IX, the lime silicate gneisses.

Specimen No. 931 is a fine grained, dark-green, schistose type with thin bands of light green epidote. The percentage of felspar and quartz is very small, and even less than in the preceding type No. 916. The main mass of the rock consists of epidote and hornblende, chlorite being a very minor constituent. In addition to the more important pale green hornblende, there is a clear colourless hornblende, and both varieties are intergrown in one crystal. The colourless hornblende shows the brighter polarisation colours and a slightly larger extinction angle. A colourless pyroxene is present, partially altered to hornblende, and more prominent in some layers than others. Granular epidote is abundant through the section, and has in part segregated into layers. The small percentage of felspar and quartz is mostly confined to these layers. Associated with the epidote crystals are a number of zoisite crystals, possessing grey and ultra-blue polarisation colours. Sphene is an important accessory, and forms thin strings of crystals in the layers of epidote. One corner of the section is crossed by a narrow vein of serpentine. The rock is an epidote-hornblende-schist, and the development of epidote, almost to the exclusion of chlorite, produces a resemblance towards the epidosite family.

IV.—GROUP III.—THE PLAGIOCLASE GNEISSES.

With a decreased percentage of hornblende and an increased percentage of felspar, the amphibolite types pass into less basic rocks which correspond to the plagioclase gneisses of Group III. In many specimens quartz becomes a more important constituent and a considerable variety of rocks, including some transitional varieties between Groups I and IV, are placed here.

KATA DIVISION.

None of the specimens examined appear to fall into this group.

MESO DIVISION.

Among the hornblende-plagioclase-gneisses are specimens Nos. 169, 170, which are light-coloured, coarse-grained rocks, in which the hornblende appears as small schlieren in the light-coloured base, and forms about 16 per cent. of the rock. The base contains quartz and alkali felspar in addition to the plagioclase. These specimens also contain fragments of much larger schlieren composed of dark amphibolite or green pyroxene. In the proximity of the amphibolite schlieren there is a band containing epidote, calcite and lawsonite along which the hornblende is partially altered. The alteration (Pl. XL, fig. 4) takes place first to a colourless hornblende and then into an aggregate of epidote, lawsonite and calcite. The pyroxene in the pyroxenic schliere shows alteration to hornblende, and there is in addition a separation of calcite when fragments of pyroxene are set in a network of calcite.

Specimen No. 378 is a pink hornblende-felspar-gneiss, whose colour is due to the pink felspar modified by the dark crystals of hornblende and mica. In section, it has a granoblastic structure and a schistose texture. The colourless constituents include quartz, clear microcline, plagioclase with accessory apatite. The dark constituents are green hornblende, greenish-brown biotite, which is partly altered to chlorite and epidote, while sphene is an abundant accessory mineral. The rock may be called a hornblende-felspar-gneiss, and on account of its content of quartz and alkali felspar it probably has a chemical composition grading towards that of Group I, the alkali felspar gneisses.

No. 259 is a hornblende-plagioclase-gneiss, which is more basic than No. 378, and probably grades in the opposite direction towards the group of amphibolites. No. 378 contains pink felspar in the hand specimen, but No. 259 possesses more hornblende and white felspar. No. 259 also possesses a coarser grain size, and some of the hornblende crystals are 4mm. wide. In section, the large hornblende crystals are green and bluish-green in colour, ragged in outline, and frequently contain inclusions of biotite. Some are partially broken across the biotite inclusions, and epidote has developed in places along the strained portions of the hornblende. Biotite is very subordinate to hornblende, and epidote has developed from the crushed biotite. Some of the epidote is finely granular, and some of it occurs in grains and crystals. Quartz is subordinate to felspar, which consists of an acid oligoclase and untwinned felspar. The felspar possesses myrmekitic structure, but it is free from products of decomposition. Quartz and some of the felspar shows strong undulose extinction. Accessory grains of apatite, allanite, and sphene are present.

Specimen No. 240 is a biotite-plagioclase-gneiss, and another example with affinities to the amphibolite group. It is a grey schistose rock, in which the dark constituents, biotite, and hornblende are subordinate to the white minerals. In section, the flakes of brown biotite are arranged parallel with the schistosity, and are in large excess over the green hornblende. There is a small amount of green chlorite and colourless lawsonite interlaminated with the biotite. Quartz is present, and the andesine felspar is quite clear, except for a few crystals which possess cloudy micaceous alteration products.

An exceptional biotite-hornblende-felspar-gneiss is specimen No. 956. The hand specimen is a dark schistose rock, showing glistening biotite, and is finer grained than most of these rocks. In section, the hornblende is quite distinct from the granular green variety of the typical amphibolites. It occurs in ragged, acicular crystals, and the colour of the prisms is mostly green and pale green. Some prisms show a pleochroism from greenish-blue to blue, indicating a change to glaucophane. In addition to the large crystals, it also occurs as fine acicular needles. Its polarisation colours are unusual. In many cases there is no position of absolute extinction between crossed nicols; but a position of 30° to 40° to the cross wires shows ultra-blue colours. While the polarisation colours appear to be low, they are interfered with by the colour and dispersion of the crystal. The biotite possesses an unusual colour, which changes in cross-section from a reddish-brown to a biscuit-brown. The crystals possess an unusually ragged outline, and contain minute dots of discharged ilmenite. The amount of felspar appears to be a little greater than in the typical amphibolites. The felspar crystals are mostly untwinned, some possess traces of microcline twinning and some are lamellar twinned crystals of acid oligoclase. Calcite, ilmenite, and epidote are minor constituents, and pyrite and apatite are accessory minerals. While the rock is more basic than typical members of this group, it is at the same time distinct from the amphibolites.

A different type of hornblende-quartz-plagioclase schist is No. 51. This is a grey schistose rock, in which numerous prismatic needles of hornblende and occasional small crystals of ilmenite are set in a grey groundmass. In section, the rock consists of thin, elongated crystals of green hornblende, set as porphyroblasts in a finely granulitic groundmass of quartz and felspar. The hornblende crystals are ragged with the pronounced prismatic habit. Its colour is dark green to bluish-green. Numerous small and isolated flakes of biotite have developed along some of the schistose layers. The ground mass, in which the quartz appears to predominate is very fine; and there are thin lenticles of felspar arising from it. Some of this felspar is untwinned; but some lamellæ show an extinction angle of 33° indicating a labradorite. There are scattered crystals of ilmenite and apatite. This type of schist is distinct from the other hornblende-plagioclase-gneisses, and the quartzitic nature of the ground mass suggests its derivation from a sedimentary rock.

Specimen No. 924 is another type of hornblende-plagioclase-schist, which is also more basic than typical members of this group. The base of the rock consists of densely-packed acicular needles of hornblende, with grains of epidote set in a colourless base of clear felspar and quartz. The hornblende needles have a pale green colour and an extinction of 20°. The rock also possesses relic phenocrysts of quartz and felspar, and in this way resembles a "porphyroide." Some of the felspars have an extinction of 27° indicating labradorite and some are studded with numerous small crystals of epidote. These relic crystals indicate that the rock has developed from a porphyritic igneous rock, probably a felspar porphyrite. The abundance of epidote is a feature belonging to the Epi division of this group.

EPI DIVISION.

This division includes the group of the epidote felspar gneisses. Some of these appear to grade into the Epi division of Group I, the Alkali-Felspar Gneisses, while others grade toward the Epi divisions of Groups IV, V, and IX, the Amphibolites and Edogites, the Magnesium Silicate Gneisses and the Lime Silicate Gneisses.

Typical of these epidote gneisses is specimen No. 257, in which the colour of the specimen is dominated by the green epidote. It is a green schistose rock with a banded structure and a much finer grain than preceding types. It possesses a distinct crystallisation-schistosity, and some of the bands possess a darker green colour than the average, on account of the association of chlorite and hornblende with the epidote. In section, the light coloured bands consist of granoblastic masses of clear felspar, with scattered flakes of pale chlorite and epidote. The felspar consists of microcline felspar and albite. In some bands epidote (with a little zoisite) is the most important mineral; while in others a pale green hornblende is as abundant as the epidote. The hornblende represents the residual mineral, which has survived the general alteration into epidote and chlorite. Its colour is bleached prior to this alteration; and areas of residual green mineral are observed, surrounded by colourless hornblende partly converted into chlorite. Sphene and apatite are present, and a few epidote grains possess a reddish-brown nucleus of allanite.

In a similar specimen, No. 157, some of the bands of pink felspar are broader, being as much as 5mm. wide, while others are darker and possess a larger percentage of hornblende. In this case, and in No. 522, quartz is present. In No. 522, the pale green hornblende changes into a colourless hornblende prior to its alteration to epidote and chlorite. Many of the epidote grains contain a reddish-brown nucleus which is probably allanite.

A coarser-grained type of the same class of rock is No. 726, in which the pink bands of felspar are 2½ cm. wide. No. 726 is a handsome rock, whose colour is dominated by the pink felspar, but contains disseminated patches of bright green epidote. In addition to the pink bands, there are bands of green chloritised hornblende with a silky sheen. In section, there is a little cloudy untwinned felspar, which may be orthoclase, and lamellar-twinned oligoclase-albite. The development of epidote within some of the plagioclase indicates that it has been partly derived from felspar. Pale decolourised hornblende is present, and the abundant chlorite and some of the epidote has been derived from it. Quartz is absent in this case, but large grains of apatite and zircon are present.

Of different appearance is specimen No. 598, a pink and green massive boulder containing large porphyroblasts of pink microcline up to 3cm. in length and over 1cm. in width, set in a rather coarsely-crystalline base of pink felspar, bright green epidote, and dark-green chlorite. The general appearance is somewhat similar to a pink porphyritic granite, except that there is a general absence of quartz. The resemblance is more strictly to a felspar-porphyry, from which it has probably been derived. The large porphyroblasts show the irregular wedge-shaped twinning of microcline, with small inclusions of quartz, plagioclase and sphene. The character of porphyroblasts has been confirmed by a determination of the alkalies by Mr. J. C. Watson, in the Victorian Geological Survey laboratory, which gave :—

K_2O ... ... 14·04 per cent.
Na_2O ... ... ·66 ,,

The felspar in the base of the rock consists of lamellar-twinned plagioclase and subordinate untwinned felspar. Sometimes it shows cataclasis and a partial development of myrmekitic structure, and sometimes bent lamellæ. Its extinction angle measures up to 14° and it is probably an oligoclase. The green chlorite and epidote are bunched together in aggregates, and of these two minerals, epidote is the more abundant, forming large idiomorphic crystals. Sphene and apatite are accessory minerals, and the rock can be classed as an epidote-felspar-gneiss. The presence of large crystals of microcline indicate a gradation towards the group of the alkali felspar gneisses (Group I).

A related rock is No. 954, in which the porphyroblasts of microcline are much smaller. The grain size is less than half that of No. 598, and the appearance is more granulitic. The epidote and chlorite are more or less evenly distributed through the section, producing the darker colour as opposed to the pink colour of the preceding specimen. The aggregated amount of epidote and chlorite is less than in previous examples, and the chlorite is more abundant than epidote. Crystals of sphene accompany the epidote. Microcline occurs in base as well as forming the porphyroblasts, and contain numerous inclusions of albite, with a ragged and irregular shape, after the manner of graphic structure. There is a considerable amount of untwinned orthoclase, and a subordinate amount of plagioclase. The abundance of microcline and the decreased amount of epidote bring the rock into the group of the alkali felspar gneisses, and it may be called a chlorite-microcline-gneiss.

Another porphyroblastic epidote-felspar-gneiss is No. 590; but it differs from the two preceding specimens in possessing a marked schistose structure. It consists of porphyroblasts of pink felspar, set in a base coloured green by epidote. The porphyroblasts consist of granoblastic aggregates of untwinned and microcline felspar. The clear base consists of felspar with a few grains of quartz and a subordinate amount of plagioclase. Coarse crystals of epidote are abundant and grouped in clusters with chlorite and a little zoisite. Ilmenite has been altered to leucoxene.

Specimen No. 910 is a different type, and may be described as an epidote-felspar-breccia. It is a very dense, fine-grained, pale-greenish rock studded with minute porphyroblasts of felspar. The thin section possesses a uniform pale-green colour, and consists of angular crystals of felspar set in a dark semi-opaque mass of epidote. The general appearance is that of a breccia and the felspar is water clear, partly twinned and partly untwinned. Some of the lamellar-twinned individuals have an extinction angle of 16°. Here and there are larger crystals of epidote, which are more transparent than the base, and consequently show brilliant polarisation colours. Under high powers the base of the rock is seen to consist of closely packed minute grains of epidote set in a base of clear felspar.

Specimen No. 592 is a massive, pale-greenish rock, somewhat similar in appearance in section to the coarse-grained variety, No. 726. It contains coarse crystals of partially altered hornblende, epidote (sometimes intergrown with allanite), chlorite and felspar. The rock is brecciated, and the fragments are separated by veins of quartz and felspar, darkened by finely granular epidote.

Specimen No. 591 is an epidote-felspar-gneiss, which has a pale-green colour and a schistose structure. In section, it shows the helical structure commonly seen in phyllites and mica schists. There are a few small felspar porphyroblasts, some of which are cracked and broken, and show various stages in breaking down into a finely granulitic mass. Some felspars are untwinned, and some are acid plagioclase. There are also a few porphyroblasts of allanite. The bulk of the rock consists of the finely granulitic base enveloping the wavy bands of dark granular epidote, similar to that in No. 910. Chlorite is present, and interwoven with the granular epidote, and there are occasional crystals of sphene. The specimen assumes a dark colour on the one side, where the amount of felspar decreases and the rock passes into an epidosite.

A further stage of epidotisation exists in specimen No. 589. This specimen retains the schistose structure and possesses traces of green hornblende. The felspar is subordinate, and there are bands of well crystallised epidote, as well as bands of finely granular epidote. Lawsonite is also present, and has been derived from the felspar. In addition there is a little zoisite and abundant sphene.

With the decrease in the percentage of felspar, the colour of the rock deepens, and a dark-green type, like No. 599, is produced. It differs from Nos. 157, 257, and 522, in possessing a massive structure. It has an increased percentage of chlorite, and possesses relationships with the epidote-chlorite-schists of Group IV. Epidote is the most abundant mineral, and, together with the decrease in felspar, indicates a transition towards the epidosites, the Epi division of Group IX, the lime silicate schists. Chlorite is much more abundant than in previous specimens, and there is only a trace of hornblende. Quartz is present, but subordinate in amount to the felspar. Both quartz and felspar show cataclasis, and some crystals appear in polarised light as fine granulitic aggregates. Ilmenite is present, and its association with sphene is another point of resemblance with the amphibolite group.

With the decrease of both chlorite and felspar, a massive green rock of epidosite is produced. No. 255 is an example of this class, consisting chiefly of epidote. The section has a uniformly yellowish-green colour, due to the epidote. Quartz is present but very subordinate. A little pale hornblende exists as relic crystals, and a little chlorite is intergrown with the epidote. Sphene, with associated magnetite, is an abundant accessory mineral, and a little calcite is present. This rock is a member of the Epi division of Group IX, the lime silicate rocks.

V.—DESCRIPTION OF PLATES.

Plate XL.

Fig. 1.—No. 520, an amphibolite in which the hornblende shows a mottled appearance, due to the separation of blue hornblende from the green hornblende. Mag. 35 diams.

Fig. 2.—Veins of lawsonite traversing a gabbro gneiss No. 515. Mag. 35 diams.

Fig. 3.—Amphibolite No. 941, in which granulitic hornblende has developed from large crystals of hornblende. The nicols are crossed, and the large crystal which occupies most of the field is nearly in a position of extinction, while the granulitic hornblende appears light due to its bright polarisation colours. Mag. 35 diams.

Fig. 4.—No. 169, in which a crystal of hornblende is partially altered to a mixture of calcite, epidote, and lawsonite. Mag. 35 diams.

Plate XLI.

Fig. 1.—No. 50, hornblende-plagioclase-gabbro gneiss.

Fig. 2.—No. 339, garnet-hornblende-plagioclase-gabbro gneiss.

Fig. 3.—No. 969, saussurite-gabbro gneiss with augen of saussurite.

Fig. 4.—No. 721, segregation vein of hornblende, felspar and subordinate quartz in amphibolite.

[With Two Plates.]

Sydney: Alfred James Kent, Government Printer—1923.

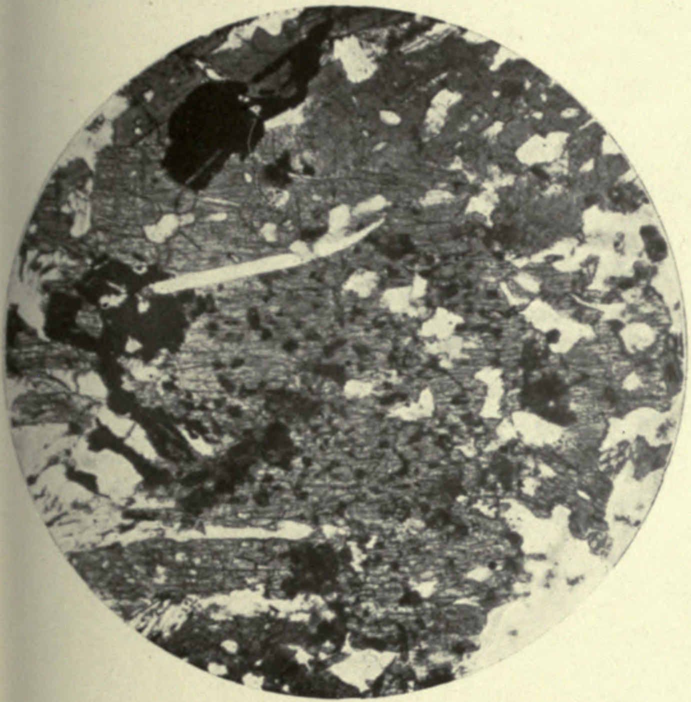
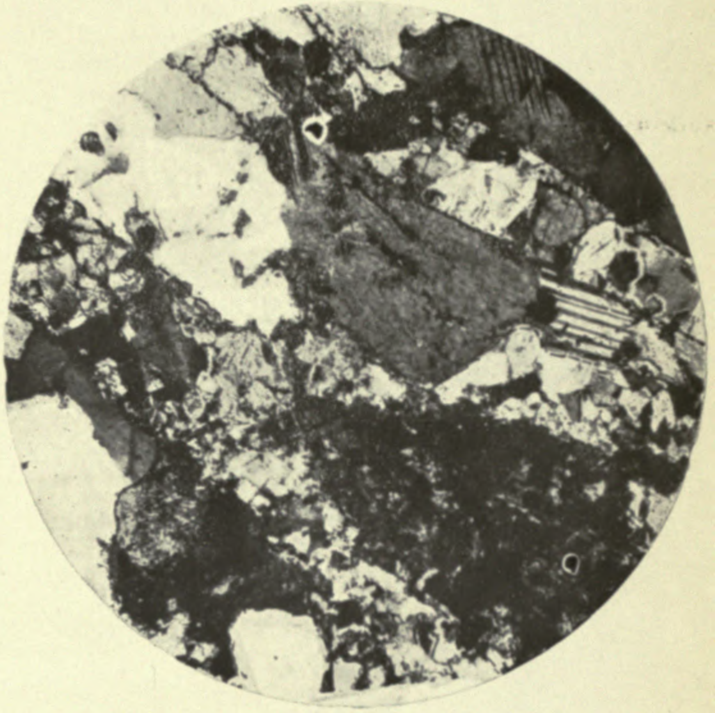


Fig. 1.



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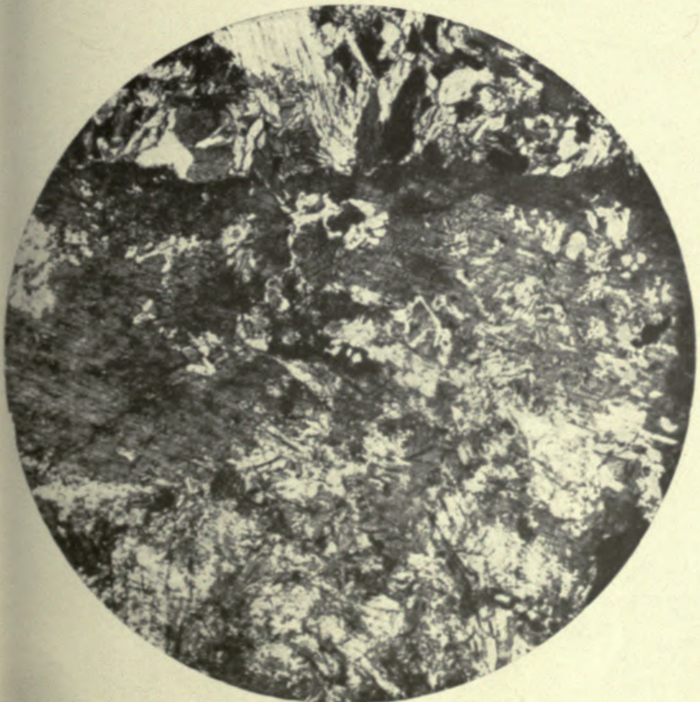

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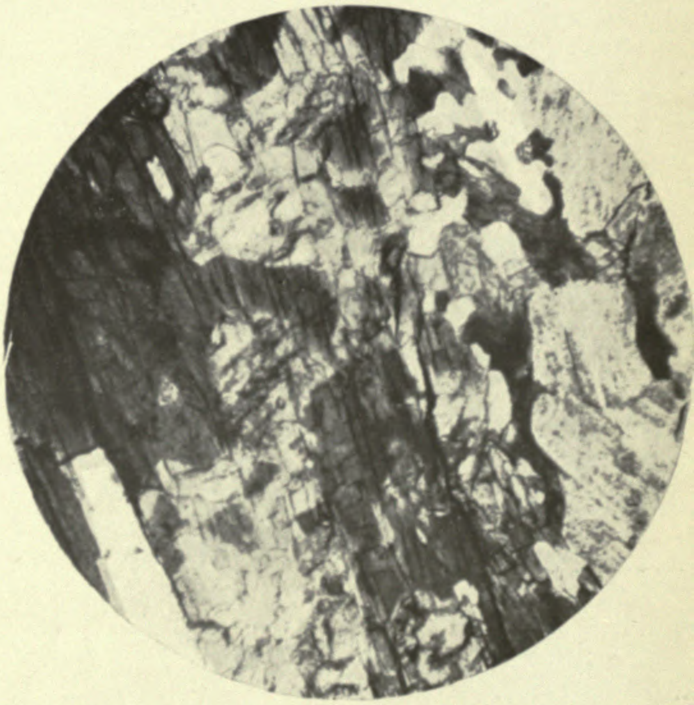

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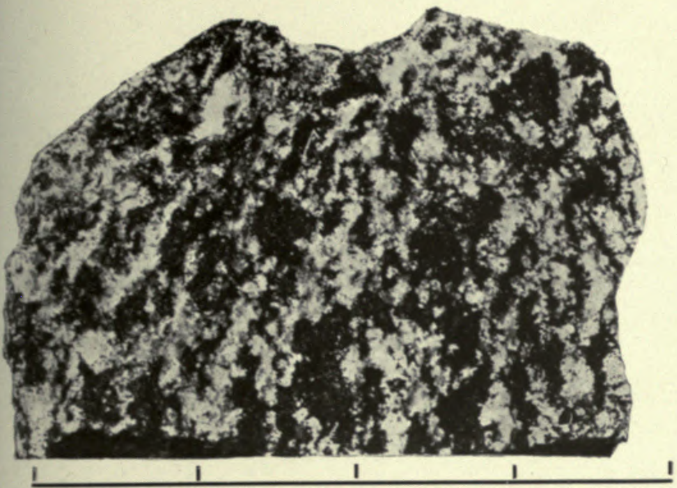

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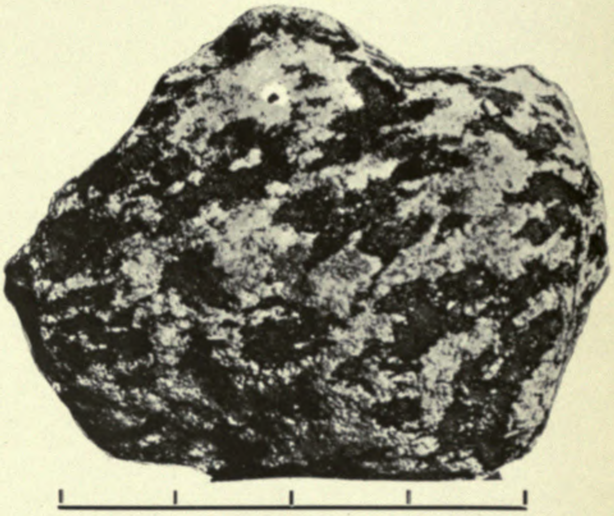

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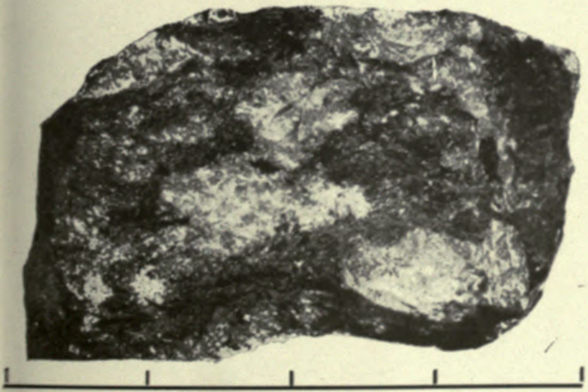

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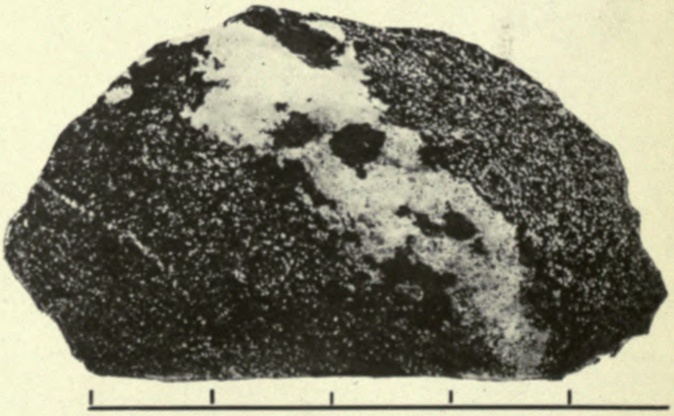

Fig. 4.

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AUSTRALASIAN ANTARCTIC EXPEDITION
1911-14.

UNDER THE LEADERSHIP OF SIR DOUGLAS MAWSON, O.B.E., B.E., D.Sc., F.R.S.

SCIENTIFIC REPORTS.

SERIES A.

VOL. III.

GEOLOGY.

APR 13 1927

PART V.

MAGNETITE GARNET ROCKS FROM THE MORAINES, CAPE DENISON, ADELIE LAND,

BY

ARTHUR L. COULSON, M.Sc., F.G.S.

WITH TWO PLATES.

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I.—INTRODUCTION.

The rock specimens, which are described below, are part of the collection obtained by the Australasian Antarctic Expedition from the glacial moraines at Cape Denison, Adelie Land. They are schists and gneisses which are chiefly characterised by an abundance of either magnetite or garnet or both. One specimen of epidote-magnetite-schist, No. 989, shows well-developed glacial striæ.

The descriptions are presented in order of relative predominance of magnetite to garnet. In the first two examples, garnet is absent but it forms 40 per cent. of the rocks towards the end of the series. The paper is concluded with the description of an interesting type containing tourmaline, magnetite, and cordierite.

The terms "gneiss" and "schist" are used in the sense defined by Holmes.[*] Grubenmann's usage[†] of the terms "texture" and "structure" is adhered to. In this, the structure is understood to be determined by the form and relative size of the components of the rock. He adds that the structures appear to be functions of the chemical composition of a rock, and of the magnitude of the temperature and pressure and the time interval during metamorphism; and are also dependent on the strength, ability, and speed of crystallisation of the minerals developed. The texture is the spacial arrangement of the constituents, and he states that the textures are not so much dependent on the nature of the rocks as upon external circumstances.

II.—PETROGRAPHY.

1. Mineral Composition.

Rosiwal determinations of some of the specimens have been made in order to express quantitatively their mineralogical content. These measurements were made on sections cut at right angles to the schistosity and the results are expressed in Table I. Generally it was found expedient to determine the quartz and felspar together. In Table I below, iron ore includes magnetite, ilmenite, pyrite, &c., while "p" signifies the presence of a mineral in small quantities. A Rosiwal determination of a magnetite-garnet rock from Broken Hill, New South Wales, is added for comparative purposes.

In some rocks, mostly of fine-grained nature, the magnetite percentage alone was determined. These form Table II, and Table III gives the specific gravities of the remaining specimens. The figures for the various minerals as stated in percentages present.

Table I.

Rock number	149	304	814	245	288	102	348	B.H.
Specific gravity	3·29	2·99	3·07	3·27	2·97	3·33	2·98	3·81
Iron ore	23·0	11·9	14·7	17·9	6·2	21·2	8·4	42·5
Garnet	12·2	7·9	12·6	15·6	6·3	40·8	20·5	23·5
Quartz	58·3	65·1	65·8	55·6	32·4‡	36·0	29·0	19·8
Felspar					45·0‡	...	29·0	...
Cordierite	...		...	...	...	...	...	...
Mica	5·5	14·7	6·6	9·2	9·7	...	13·1	...
Apatite	1·0	0·4	0·3	1·2	0·4	2·0	p.	14·2
Epidote	...	...	p.	0·5	p.	...	p.	...
Zircon	p.	p.	p.	p.	p.	...	p.	p.
Calcite	...	...	...	...	...	...	p.	...

---

[*] "The Nomenclature of Petrology." A. S. Holmes, London, 1920, p. 107.

[†] "Structur und Textur der Metamorphischen Gesteine." U. Grubenmann. Fort. der Min., Krist. und Pet., Band II, 1912, p. 209.

[‡] Approximate.

TABLE II.

Rock number	576	912	294	55	889
Specific gravity	3·12	3·31	3·14	3·11	3·13
Iron ore	23·4	32·4	33·0	18·9	26·9

TABLE III.

Rock number	765	926	296	989	527 (A)	933	827	181
Specific gravity	3·97	2·93	2·94	2·93	3·00	2·83	3·26	2·96

2. DESCRIPTION OF ROCK SPECIMENS.

No. 765.—This is a dark, heavy, and fine grained rock, composed of a mass of magnetite, hematite, and quartz, through which run bands of quartz and minute hematite flakes. Small fragments of the rock are strongly magnetic. Its specific gravity is 3·97, the highest for the group.

Microscopically, the quartz occurs in very fine grains, which show strain polarisation colours and which contain myriads of inclusions of micaceous hematite or "eisenglimmer." While eisenglimmer occurs abundantly within the quartz bands, magnetite is the chief constituent of the rock. The structure is granoblastic and the texture is schistose. The rock is a *Magnetite-Schist.*

No. 926.—This is a dark greasy-looking rock, extremely fine grained and possessing a well-developed crystallisation-schistosity.

Biotite is one of the chief constituents, occurring in very minute flakes and showing no trace of any alteration to chlorite. Magnetite is fairly abundant and with quartz makes up the bulk of the remainder of the rock; it is usually xenoblastic in form and generally of small dimensions. Quartz shows strain polarisation and contains minute inclusions of magnetite, and epidote. This latter mineral is disseminated through the rock in minute roughly circular grains. Calcite occurs in moderately large masses and surrounds epidote, quartz, magnetite and biotite; the characteristic cleavage is well developed. The structure is lepidoblastic to granoblastic and the texture is schistose. The rock is a *Biotite-Magnetite-Schist.*

No. 576.—This is a gneissic type in which magnetite, epidote, biotite, quartz, and pink orthoclase can be recognised in the hand specimen. The structure is heteroblastic. Magnetite is important and occurs in xenoblastic individuals with a roughly parallel alignment. Garnets are rare; they cannot be recognised in the hand specimen and are confined to certain bands in the section. Such as are present are the fragmentary remains of large crystals which have been mostly altered to chlorite, quartz, and magnetite. This is a common alteration in the suite of specimens and will be dealt with later. The colour scheme of the biotite is X, light green, Y and Z, dark green. Sometimes it has altered to chlorite, frequently showing the indigo blue polarisation colours of clinochlore, and magnetite. Quartz is abundant and shows cataclasis and strain polarisation. Orthoclase felspar is common but much kaolinized and sericitised. Epidote occurs in numerous granular aggregates, usually almost opaque, and a very strong light is necessary to observe its characteristic polarisation colours. Apatite is common as small rounded grains. The rock is *Micaceous-Magnetite-Gneiss.*

No. 912.—This is a schistose type, dark-coloured, and easily cleaved. It is extremely fine grained and it possesses a lustrous appearance owing to the presence of white mica. Flakes of the rock are strongly magnetic.

Microscopically, the structure is lepidoblastic. Magnetite crystals, which constitute nearly a third of the rock, are xenoblastic in outline, especially in the larger grains. Occasional minute flakes of micaceous hematite (eisenglimmer) are recognised and ilmenite is intergrown with the magnetite. Garnets are moderately abundant but they are small and much fractured and contain inclusions of magnetite. Green biotite is common and sometimes exhibits pleochroic halos which are too indistinct to measure. Quartz is an important constituent and contains fluid and magnetite inclusions. The fluid inclusions generally have an arrangement parallel to the schistosity. Scaly sericite, chlorite, epidote, and accessory apatite form the remainder of the rock, which may be called a *Magnetite-Schist.*

No. 296.—This is a dark greasy-looking rock, extremely fine grained and traversed by a few lenticular bands composed mostly of quartz and epidote. It possesses a very definite crystallisation schistosity.

The structure is both granoblastic and lepidoblastic. Magnetite is extremely abundant, occurring in little xenoblastic individuals with linear development and also in larger porphyroblastic grains (up to 0·3 mm.). It is disseminated through the rock as well as segregated in thin bands. Small red flakes of micaceous hematite also occur. Garnets are very small and idioblastic, their averages absolute diameter being about 0·4 mm. Quartz is the most abundant constituent and reduces the specific gravity (2·93) below the average. Biotite is present as small flakes, while epidote is restricted to certain bands as xenoblastic grains. Felspar is absent. The rock is *Quartz-Magnetite-Schist.*

No. 989.—Macroscopically the rock is dense and dark-coloured, being traversed by a few epidotic bands. Little porphyroblasts of magnetite can be seen in the ground mass of the rock.

The structure is granoblastic and the texture is schistose. In most respects the rock is similar to the preceding quartz-magnetite-schist, No. 296. The garnets, however, show two kinds of alteration, one of which has produced chlorite and the other epidote. Both changes can be observed in all stages of completion. The biotite is irregular in shape and frequently contains inclusions of recrystallised quartz. It has no very definite relationship to the schistosity and shows all stages of alteration to chlorite with concomitant production of magnetite. Epidote occurs in granular aggregates in addition to that formed directly from the garnet, and the rock may be called an *Epidote-Magnetite-Schist.*

No. 527. (A).—This is somewhat similar to the micaceous magnetite gneiss, No. 576, in the hand specimen and shows a very contorted banding. Pink orthoclase is prominent.

The main structure is granoblastic but relic, zig-zag and lenticular structures are observed microscopically. Magnetite is abundant and mostly in irregular xenoblasts, while a few flakes of micaceous hematite may be observed. A few garnet relics have survived the alteration to quartx, magnetite, and chlorite. In some cases the outline of the original garnet is preserved (Plate II, fig. 1). Much of the chlorite has been derived from the garnet but part has arisen from the alteration of biotite with the accompanying production of magnetite. Muscovite is sometimes intergrown with chlorite Fine granular quartz grains contain inclusions with an arrangement parallel to the schistosity. Orthoclase is present as large relic crystals which are simply twinned and untwinned. Epidote and apatite are present. The rock is a *Chlorite-Magnetite-Gneiss.*

No. 933.—The hand specimen is a well-laminated greenish rock with an abundance of biotite, chlorite, and muscovite. Biotite and chlorite form flaky aggregates which give the rock a spotted appearance. Quartz occurs in convolute veins which follow the schistosity for some distance and then break across it. The laminae of the rock are curved at one end as the result of bending and shearing rock movements which may have accompanied the infiltration of the quartz.

The structure is lepodoblastic but relic and cataclastic structures are also present. Magnetite is abundant. Small garnets show the usual development of quartz, magnetite, and chlorite, when examined under the high power, but not nearly to the same extent as in No. 527 (A). Quartz occurs both in large grains in the vein and in small grains with an elongation parallel to the schistosity. It exhibits strain polarisation and the larger grains show cataclasis. Biotite contains a few pleochroic halos around minute zircons and muscovite is very abundant. Granular epidote is largely intergrown with chlorite. The siliceous veins contain biotite and magnetite and relic felspars which are much kaolinised and penetrated by newly formed quartz. The twin lamellae can sometimes be picked out (Plate II, fig. 2). The rock is a *Mica-Magnetite-Schist* and has the lowest specific gravity of the group (2·83).

No. 294.—This is an interesting magnetite-schist with contorted banding. In part slight shearing movements have resulted in the fracturing of the bands. Thin quartz veins cut across the bands and are later than the fundamental metamorphism.

The structure of the rock is granoblastic and the texture is schistose. Magnetite forms approximately one-third of the rock. Garnets have been fairly common but are mostly altered. By far the greater part of the chlorite is derived from the biotite which was originally very abundant. Epidote is present and quartz is common. In the veins, the quartz shows brush polarisation and a larger grain size. Felspars are present but they are so completely kaolinised that it is impossible to identify them.

No. 55.—This is a fine grained, dark, heavy crystalline rock of specific gravity 3·11. It possesses a strongly developed crystallisation schistosity. Glistening white mica on the cleavage planes gives a lustrous appearance to the rock. Fragments of the rock are strongly magnetic.

The structure is both granoblastic and lepidoblastic. Magnetite is abundant and ilmenite is also present as shown by the presence of white leucoxene. Hematite occurs but the bulk of the 18·9 per cent. of iron ore is magnetite. Garnets are abundant, the chief alteration being magnetite, though chlorite is also formed. A green variety of biotite is very common and usually associated with muscovite, which appears to be a later product than the biotite. The latter is much altered to chlorite. Quartz shows strain polarisation and sometimes its recrystallisation has split flakes of biotite from their parent crystals. Felspar is present but is largely kaolinised. It sometimes exhibits the remnants of a fine twinning. Apatite is present. The rock is a *Mica-Magnetite-Schist.*

No. 889.—This specimen possesses a moderate crystallisation schistosity. On one side there is a well-developed shear face along which abundant ilmenite is developed. In the mass of the rock, blue cordierite can be seen.

Two sections were made of this rock, one of which was at right angles to the schistosity. The magnetite percentage (26·9) was obtained from the latter section. Intergrown with the magnetite, is a fair amount of hematite but ilmenite is not abundant in the sections. The rock was originally rich in garnet which has been mostly altered to a mass of quartz, magnetite, and either biotite or muscovite. Biotite is usually accompanied by felspar and shows alteration to magnetite. Magnetite has also been developed along a series of sub-parallel lines in the garnet (Plate II, fig. 3), and where these meet, the alteration is complete.

The biotite is a greenish-brown variety and contains numerous pleochroic halos. Occasionally there is a slight development of chlorite from biotite but a much commoner alteration has produced magnetite and muscovite. The last mineral appears to be derived from either the garnet or the biotite. Cordierite is abundant in the section cut at right angles to the schistosity. It is distinguished from quartz by faint pleochroic spots and its pronounced signs of alteration. The bulk of the felspar is andesine but some is more calcic, probably approaching labradorite. One fine example of a crystal of andesine shows a graphic intergrowth with quartz. Apatite is abnormally biaxial in its interference figure. The structure is heteroblastic and the rock is a *Magnetite-Garnet-Schist.*

No. 149.—This rock shows a pronounced gneissic banding. It is a medium grained rock and flakes readily owing to the amount of mica. Quartz, garnet, felspar, mica, and magnetite can be recognised and the mineral proportions are given in Table I. Magnetite with intergrown ilmenite forms 23 per cent. of the rock. The ilmenite is recognised by its alteration to leucoxene. Sphene is doubtfully present. Garnet, magnetite, and also apatite contain inclusions of one another. Some garnets are idioblastic and others show evidence of resorption. Quartz, plagioclase, and orthoclase are present in approximately equal proportions. The plagioclase, is mostly labradorite, and, like the orthoclase, is slightly kaolinised. Quartz contains numerous opaque inclusions of iron oxide.

The biotite is interesting. It is a yellowish-brown variety occurring in large sporadic flakes which contain radioactive inclusions surrounded by beautiful pleochroic halos (Plate II, fig. 4). All the inclusions are of considerable dimensions relative to the halos which surround them and their longer and shorter axes have been measured. The radii of the halos in the following table are the average of two or three measurements of the distance from the edge of the inclusion to the outer edge of the halo. A 4 cm. (× 45) objective lens was used in conjunction with a Beck micrometer eye-piece and the measurements given below are in millimetres.

TABLE IV.

Radius of Halo.	Remarks.	Dimensions of Nucleus.	Remarks.
·043	Indistinct	....	....
·040	Very distinct	·035 x ·020 ...	Wedge-shaped.
·040	Very distinct	·040 x ·040 ...	Circular.
·039	Very distinct, slight difference in colour, being lighter near nucleus.	·033 x ·033 ...	Circular.
·039	Lighter area next nucleus (to about ·009mm. from the edge).	·039 x ·031 ...	Rectangular, straight extinction.
·038	Very distinct	·026 x ·020 ...	Wedge-shaped, straight extinction (?)
·024	Fairly distinct	·042 x ·037 ...	Oval.
·017	Distinct	·010 x ·010 ...	Circular.
·016	Indistinct	·020 x ·016 ...	Oval.
......	Indistinct	·033 x ·020 ...	Oval.
......	Indistinct	·020 x ·013 ...	Oval.

In the measurements made by Joly* a correction is made for the nucleus on the assumption that the nuclei are zircon and that they are sensibly spherical. In this rock, however, the nuclei are too large and such corrections would not be valid. The halos are remarkable even in colour, but in two cases there is an appreciable difference in colour, which, however, is too slight for accurate measurement. The inclusions show high order polarisation colours and appear to have straight extinction, thus suggesting zircon.

---

* "Genesis of Pleochroic Halos." J. Joly. Lond. Roy. Soc., Phil. Trans., Series A, vol. 217, pp. 51–79, 1917.

Joly and Fletcher* give the radii of halos in biotite as follows :—

Uranium—Ra C	Ra A	Thorium—Th C.	Th X
·0326	·0222	·0397	·0263

On the basis of these measurements the first six halos in the above Table IV are probably due to Th C and the origin of the others is doubtful.

The structure of the rock is heteroblastic and it may be called a *Magnetite-Garnet-Gneiss.*

No. 147.—Part of this specimen is a dark magnetite gneiss and part is a light-coloured acidic rock. It exhibits a pronounced example of lenticular structure.

The acidic part shows large crystals of quartz, fibrous sillimanite, magnetite, biotite, plagioclase, and orthoclase. The dark banded part contains abundant magnetite, garnet, quartz, cordierite, and felspar. Magnetite is more abundant in the dark part than in the light, but is especially plentiful at the junction.

In the dark gneissic portion the magnetite encloses cordierite, apatite, and sillimanite. Ilmenite and rutile are also present. Garnet, which is absent from the acidic part, contains inclusions of quartz, magnetite, and apatite, and also shows evidence of resorption. The felspar has an extinction angle of 12° and a refractive index usually greater than quartz. It thus suggests andesine. Quartz shows strain polarisation. Biotite shows evidence of resorption and sometimes contains radioactive inclusions; one perfect example has a halo with a radius of ·037 mm. and is ascribed to Th C. †

Cordierite is abundant; at times it is altered to a pinitic mica with an absence of any basal lamination, and at others it has given rise to a serpentinous product with a radial arrangement and brush polarisation. Sillimanite is usually intergrown with the biotite and appears to have developed from it, more especially in the acidic part. It occurs in the fibrous form and also in stouter prisms, with the slowest ray parallel to the prism axis. Orthoclase and andesine occur in the acidic part. Some crystals of epidote are present with a darker margin which shows higher polarisation colours and stronger pleochroism than the central portion. They usually adjoin magnetite crystals and the darker margin contains a greater percentage of iron. The structure of the gneissic part is heteroblastic and the rock is a *Magnetite-Garnet-Schist.*

No. 827.—This is a gneissic type with a discontinuous banded structure, the various bands differing greatly in mineral content. The following minerals can be identified in the hand specimen :—Quartz, magnetite, blue cordierite, felspar, sillimanite, biotite, and pink garnet. The distribution of the magnetite is especially irregular. A central band through the rock is composed of magnetite, altered cordierite, pink garnet, and quartz. Biotite is plentiful on both sides of this band.

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* "Pleochroic Halos." Phil. Mag., 6th Series, Vol. XIX, p. 633, 1910.

† Jolly and Fletcher, *op. cit., p.* 633.

Magnetite has crystallised out later than the biotite and it appears to have split off fragments of biotite by crystallisation between the cleavage flakes. The magnetite does not appear to have been derived from the biotite as there is a general absence of any minerals accompanying such a change. Flakes of green chlorite with a magnetite are rare. Garnets usually show round edges due to resorption. Quartz is abundant and shows strain polarisation. Apatite is present, and possible cyanite. Little sillimanite and no felspar can be observed in the section on account of the very variable distribution of the minerals in the rock. Fragments from the hand specimen show that the felspar is an acid plagioclase. Cordierite gives rise to a yellowish alteration product. One large zircon crystal, ·20 x ·15 mm., with uniaxial figure and high colours, is observed. The structure is heteroblastic and the rock is best described as a *Magnetite-Garnet-Gneiss.*

No. 181.—This is a distinctive and banded variety with numerous dark porphyroblasts of magnetite (Plate I, fig. 1). Their longer axes are parallel to the well-developed schistosity and at times measure 14 x 7 mm. One large elongated crystal of tourmaline is noted which possesses the trigonal cross-section and characteristic absorption. A green chloritic mica is the only other mineral occurring in large masses. A similar rock is illustrated (Plate 1, fig. 2), in which the magnetite porphyroblasts have been elongated into a pronounced linear structure.

Microscopically the rock is composed of bands of minute quartz and garnet, quartz, and felspar and biotite crystals. The magnetite individuals are studded with numerous inclusions of garnet, biotite, quartz, and altered felspar. A little rutile is intergrown with the magnetite and occasionally there is a slight alteration to limonite. Garnets are numerous but their size is small; some of the grains, especially the smaller ones, show anomalous double refraction. When a band of quartz and garnet meets a magnetite porphyroblast, it divides into two and surrounds the porphyroblast. Green biotite is common and associated with green chlorite. There is a distinctive yellowish-brown biotite which is rare relative to the green variety. Muscovite is present in small amount. Plagioclase and orthoclase are present and the former ranges down to andesine. The felspar is frequently kaolinised. Epidote is present. Some crystals suggest cordierite but there is an absence of brown pleochroic spots. Quartz is abundant, while apatite is a common accessory. No tourmaline is present in this section. The rock is a *Porphyroblastic-Magnetite-Garnet-Gneiss.*

No. 304.—This is a schistose rock, to which is attached, like No. 147, part of a coarsely crystalline vein or lens composed of quartz, felspar, garnet, magnetite, and also micaceous hematite.

Magnetite forms 11·9 per cent. of the rock and it contains inclusions of garnet, biotite, apatite, quartz, and cordierite. Hematite is present and a little limonite has developed from the magnetite. No ilmenite is noted and no reaction obtained for titanium. Garnets form 7·9 per cent. and are usually idiomorphic. Biotite is abundant, forming 14·7 per cent., and frequently includes quartz and zircon. Quartz is abundant and contains numerous inclusions of garnet, magnetite, and zircon and also fluid inclusions. It shows strain polarisation and is at times difficult to distinguish from cordierite; the latter is usually recognised by the pleochroic brown spots. Such extinction angles as can be measured for the felspars are high, and these, in conjunction with a high refractory index, suggest labradorite. Though most of the felspar is clouded, there is occasionally a clear fresh felspar with an extinction angle of 10 degrees and a low refractive index which is probably albite. No sillimanite is present. The structure of the rock is granoblastic and the specimen may be called a *Magnetite-Garnet-Gneiss.*

No. 814.—This is a banded type in which the bands are narrower at the centre of the specimen than at either end. They are composed of quartz, garnet, biotite, felspar, and magnetite, and the pink colour of certain bands is due to a predominance of garnet.

Magnetite with a little intergrown hematite forms 14·7 per cent. of the section. No ilmenite occurs and no reaction was obtained for titanium. The magnetite frequently contains inclusions of quartz, biotite, and garnet and there is sometimes a rim of magnetite around a garnet crystal, while cracks in the garnets may be filled with magnetite. Garnet, which was one of the first minerals to be formed, has an average grain size of about 0·25 mm., forming 12·6 per cent. of the section. Quartz and felspar constitute nearly two-thirds of the rock. Quartz shows strain polarisation and is relatively clear with respect to the felspar; it frequently contains inclusions of apatite, zircon, and garnets. The felspar is only slightly altered and ranges from andesine to labradorite. A little orthoclase is present. The felspar contains inclusions of quartz, magnetite, and apatite. The biotite is a brown variety with numerous inclusions of garnet, apatite, and sometimes magnetite. The structure is granoblastic and the rock is a *Magnetite-Garnet-Gneiss.*

No. 245.—This is a dark schistose type in which magnetite, garnet, biotite, and quartz can be identified macroscopically.

Magnetite is an important constituent of the rock and a fair amount of ilmenite is intergrown with it. Chemical tests on this and the following specimen (No. 288) indicates the presence of titanium. Magnetite crystals enclose quartz, biotite, and garnet. Garnets (15·6 per cent.) are almost as numerous as magnetite (17·9 per cent.) and are more idioblastic though they are smaller in size (0·14 mm.) Some have been altered to quartz and micaceous products and others have produced epidote, as in No. 989. Quartz and felspar are abundant. Numerous minute gaseous inclusions in the quartz have a roughly parallel arrangement, but there are other small reddish inclusions which are possibly hematite or rutile. Both orthoclase and plagioclase are present; the latter is mostly andesine but some approaches labradorite in composition. Microcline with its typical cross-hatching is observed and the felspar is generally free from alteration. Green biotite forms 9·2 per cent. and shows pleochroic halos around minute zircons. Apatite and epidote are noted. The rock is a *Magnetite-Garnet-Schist.*

No. 288.—This rock is very similar to No. 245 in the hand specimen except that it contains some moderately large porphyroblasts of magnetite.

The garnets are mostly of smaller dimensions (0·07 mm.) than in the preceding No. 245 and they are sometimes enclosed in the magnetite. The larger porphyroblasts of magnetite are confined to certain bands; they are elongated parallel to the schistosity and contain inclusions of quartz and appear to have a little rutile intergrown with them. Felspar is the most abundant mineral present and it is much altered to an aggregate of micaceous minerals and epidote. Relics of microcline with cross-hatching are present but the greater part of the felspar is a plagioclase of composition between andesine and labradorite. Quartz shows strain polarisation and cataclasis. Biotite is greatly altered to chlorite and secondary magnetite. Muscovite has also been developed from biotite and is not symmetrically disposed to the schistosity planes. A little bleached biotite and accessory apatite occur. Granoblastic, porphyroblastic, and cataclastic structures are the chief ones present. The rock is a *Garnet-Magnetite-Schist.*

No. 102.—This is a massive type with dominating garnet. Most of it is fine grained but in parts the crystals of garnet and quartz attain considerable size.

Garnets form 40·8 per cent. of the rock and occur as irregular masses traversed by numerous cracks along which iron ore occurs (Plate II, fig. 5.) When the garnet is altered to chlorite, a larger amount of iron ore is developed. Garnet is also intergrown with magnetite and quartz; and all three minerals contain inclusions of one another. Limonite is present as a pseudomorph after magnetite and there is a fair amount of rutile intergrown with the magnetite; this is red by reflected light and probably absorbs the 1·14 per cent. of TiO_2, in the rock. Apatite is more abundant than usual and occurs chiefly with the magnetite. Quartz is abundant and contains numerous inclusions of minute iron ore individuals arranged in parallel lines. A few zircon crystals occur. The structure is diablastic and the texture is massive. It is *Garnet-Quartz-Magnetite Rock.*

No. 348.—This is a schistose variety with bands of minute pink garnets and clear quartz, which show up well from the otherwise greenish-black rock. Scattered through the rock are occasional porphyroblasts of magnetite and in this respect the specimen resembles Nos. 181 and 288.

Garnets are numerous and form one-fifth of the rock but the average size of the grains is only 0·06 mm. The chemical analysis shows that this rock contains 8·23 per cent. of MnO and it is probable that this is contained in the garnet. Magnetite occurs both as xenoblastic and idioblastic individuals which generally have their longer axes parallel to the schistosity. Felspar and quartz are present in equal proportions. The felspars are almost entirely kaolinised and their original nature is somewhat indefinite; such extinction angles as are measurable indicate andesine but orthoclase is also present. Quartz contains gaseous, garnet, and magnetite inclusions and shows strain polarisation. Green biotite is commonly altered to chlorite. Epidote and calcite, both probably derived from the alteration of the felspars, as well as apatite and zircon, are present. The structure is both porphyroblastic and granoblastic and the rock is a *Garnet-Magnetite-Schist.*

3. CHEMICAL CHARACTERS.

The table below (Table V) contains the results of three chemical analyses. A fourth analysis of the Broken Hill rock, the mineral composition of which is given in Table I, is given for comparative purposes.

TABLE V.

	I.	II.	III.	IV.
SiO_2	50·35	53·73	57·78	31·34
Al_2O_3	16·18	11·57	12·01	8·34
Fe_2O_3	13·57	13·15	7·35	32·10
FeO	5·57	14·41	4·98	6·75
MgO	1·78	2·11	1·79	0·94
CaO	1·94	1·79	2·85	7·54
Na_2O	3·14	0·15	1·70	0·11
K_2O	0·89	absent	1·47	0·05
H_2O + ...	0·50	0·80	0·69	0·52
H_2O —	0·98	0·62	0·52	0·63
TiO_2	0·49	1·14	0·73	0·40
CO_2	absent	absent	n.d.	0·01
ZrO_2	trace	trace	0·06	absent
P_2O_5	0·48	0·53	0·16	4·67
SO_3	......	absent	absent	trace
F	......	......	......	trace
Cl	......	......	......	0·09
S	trace	0·16	absent	absent
Cr_2O_3	absent	absent	absent	absent
NiO, CoO	absent	absent	trace	trace
MnO	4·12	0·24	8·23	7·08
BaO	absent	absent	trace	trace
SrO	trace	absent	0·06	pres. (spect.)
Li_2O	......	......	......	absent
V_2O_3	......	......	......	0·02
CuO	......	......	......	trace
	99·99	100·40	100·38	100·32
				less O = Cl 0·02
Specific gravity ...	2·96	3·33	2·98	3·809

I. No. 181, Porphyroblastic magnetite-garnet-gneiss, Adelie Land. Analyst, A. L. Coulson.
II. No. 102, Garnet-quartz-magnetite rock, Adelie Land. Analyst, A. L. Coulson.
III. No. 348, Garnet-magnetite-schist, Adelie Land. Analyst, A. L. Coulson.
IV. Quartz-garnet-magnetite rock, Broken Hill, New South Wales.* Analyst, W. G. Stone.

The analyses are noteworthy for their low silica as there is abundant free quartz in each case. Felspar is an equally important constituent in Nos. 181 and 348 where appreciable alkalies are present. Felspar is not recorded in No. 102 or in the Broken Hill specimen and the total alkalies are extremely small. The remarkable high content of magnetite and garnet is reflected in the high total iron. Lime and magnesia are extremely low and reflect the paucity of ferromagnesian minerals. Magnesia is almost wholly contained in the mica and the lime in the felspar and apatite. Practically no lime and magnesia is available for the garnet. In No. 102, which contains 40·8 per cent. of garnet, it can be clearly inferred that the garnet is an iron-alumina variety. In No. 181 there is 4·12 per cent. of MnO which probably replaces part of the FeO in the garnet. No. 348 contains an exceptional amount of 8·23 per cent. of manganese and the composition of the garnet may approach that of spessartite. Qualitative tests indicate the presence of considerable manganese in the chlorite magnetite schist 527A and in the magnetite garnet schists and gneisses Nos. 304, 814, 245, and 288. Rutile is recorded in Nos. 181 and 102 and may account for part or all of the titanium content. Qualitative tests revealed a fair amount of titanium in the similar rocks Nos. 245 and 288, but it proved to be absent in Nos. 304 and 814. In No. 245 the titanium percentage is ascribed to ilmenite.

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* "Geology of the Broken Hill District," E. C. Andrews. Mem. 8, Geol. Surv., N.S.W., p. 172.

Comparison with the chemical analysis of the Broken Hill rock shows great similarity. The lower silica and higher total iron of the Broken Hill rock corresponds with lower quartz and garnet percentages and higher iron ore than No. 102. Its high manganese content is a marked point of resemblance with No. 348. It is distinct, however, in its high lime and phosphorus which correspond with the measured percentage (14·2) of apatite. Its large excess of Fe_2O_3 over FeO appears to indicate more hematite than in the Antarctic types.

4. SUMMARY OF PETROGRAPHICAL CHARACTERS.

The following rocks have been described :—

Magnetite-schists	Nos. 765, 912, 294.
Biotite-magnetite-schist	No. 926.
Chlorite-magnetite-schist	No. 527A.
Mica-magnetite-schists	Nos. 55, 933.
Mica-magnetite-gneiss	No. 576.
Quartz-magnetite-schist	No. 296.
Epidote-magnetite-schist	No. 989.
Magnetite-garnet-schists	Nos. 889, 147, 245.
Magnetite-garnet-gneiss	Nos. 827, 181, 149, 304, 814.
Garnet-magnetite-schists	Nos. 288, 348.
Quartz-garnet-magnetite rock	No. 102.

Quartz, felspar, and mica are the chief minerals present in the rock suite in addition to the abundant magnetite and garnet which characterise the group. The quartz usually shows strain polarisation colours and a cataclastic structure. In a number of cases minute inclusions have a definite alignment within the individual quartz crystals which is generally parallel to the planes of schistosity.

Felspar is an important constituent, though it is totally absent in the magnetite-schist No. 912, in the quartz- or epidote- or mica-magnetite-schists Nos. 296, 989, 933, and in the quartz-garnet-magnetite rock No. 102. Orthoclase is a common constituent but microcline only occurs in the magnetite-garnet-schist No. 245, and the garnet-magnetite-schist No. 288. The plagioclase ranges from albite to labradorite and it commonly happens that an acidic and a basic plagioclase are present. Generally the felspars are much kaolinised and sericitised.

Cordierite is not common but is observed in four magnetite-garnet schists and gneisses No. 889, 147, 827, and 304. Such crystals as are seen in these sections do not exhibit any measurable pleochroic halos.

Biotite is a very common constituent, the usual variety being green in colour. Muscovite is present in some sections, notably in the chlorite-magnetite-schist No. 527A, the mica-magnetite-schists Nos. 55, 933, and the epidote-magnetite-schist No. 889. Chlorite is an important mineral and usually owes its origin to the alteration of biotite or garnet. Epidote is abundant in some of the magnetite schists but it loses importance as the ratio of garnet to magnetite increases. Apatite is a common accessory, as also is zircon.

Magnetite usually has ilmenite or hematite or rutile intergrown with it. Limonite, pyrite, and sphene also occur but the latter two minerals are not common. The percentage of iron ore ranges from 33·0 in the magnetite-schist No. 294 to 6·2 in the garnet-magnetite-schist No. 288. In most cases the crystals of magnetite are xenoblastic rather than idioblastic. In Nos. 181, 288, and 348 there are magnetite porphyroblasts and in the example in Plate I, fig. 2, a pronounced linear structure has developed from the porphyroblasts. As the porphyroblasts of magnetite have their longer axes parallel to the schistosity and contain numerous inclusions of garnet, quartz, and biotite, all of which originated during, or were recrystallised by, the metamorphism, these porphyroblasts evidently arose at the time of major metamorphism, when the conditions of pressure and temperature probably corresponded to Grubemann's meso zone of metamorphism. The chloritisation of the biotite and the kaolinisation of the felspars probably arose under later conditions of epi zone metamorphism. Stillwell * has applied a conception of metamorphic differentiation to clots of biotite and epidosite in amphibolite dykes at Cape Denison. It is possible that the same conception can be applied to the magnetite porphyroblasts, in which case they are due to local segregation of iron ore arising as a direct consequence of the metamorphism. In many instances in the suite of rocks described, magnetite has been considered as arising partly from the result of epi zone processes on the garnet and mica.

Garnet is a less constant constituent than the magnetite. It is absent in some specimens and ranges up to 40 per cent. in No. 102, where it dominates the colour of the

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* "The Metamorphic Rocks of Adelie Land." F. L. Stillwell. Aust. Ant. Exp. Scientific Reports, Series A, Vol. III, Part 1 (1918), p. 58–71.

rock. The commonest alteration of the garnet is the production of chlorite, quartz, and magnetite which is especially well displayed in the chlorite magnetite schist No. 527A. The reaction can be illustrated by the equation—

$$\underset{\textit{Garnet.}}{2\,\mathrm{MgFe_3AlSi_3O_{12}}} + 4\,\mathrm{H_2O} \rightleftarrows \underset{\textit{Chlorite.}}{\mathrm{H_8Mg_2Fe_3Al_2Si_3O_{18}}} + \underset{\textit{Quartz.}}{2\,\mathrm{SiO_2}} + \underset{\textit{Magnetite.}}{\mathrm{Fe_3O_4}}.$$

The two arrows going in opposite directions means that the equation representing a reaction is reversible.

In this composition of the garnet the ratio of Mg to Fe is assumed to be as 1 to 2, and the ratio of Fe to Al as 1 to 1. The chlorite is also assumed to be an isomorphous mixture of the two silicate molecules, $\mathrm{H_4(MgFe)_3Si_2O_9}$ and $\mathrm{H_4(MgFe)_2Al_2SiO_9}$ in the proportions of 1 to 1. Chemical work has indicated, however, that the garnet contains manganese in many cases where this change is observed. On alteration, it is probable that the manganese enters the composition of magnetite rather than the chlorite, producing manganmagnetite, the composition of which is expressed by $\mathrm{(FeMn)O, Fe_2O_3}$.

While quartz, chlorite, and magnetite are the usual alteration products of garnet, magnetite was the sole recognisable product, in some cases thus indicating the migration of quartz and chlorite. In the magnetite-garnet-schist No. 889, there is a production of quartz, magnetite, and either biotite or muscovite. This may have been attained by a reaction between garnet and the microcline or orthoclase in the following manner :—

$$\underset{\textit{Garnet.}}{\mathrm{Fe_3Al_2Si_3O_{12}}} + \underset{\textit{Orthoclase.}}{\mathrm{KAlSi_3O_8}} + 2\,\mathrm{(OH)} \rightarrow \underset{\textit{Muscovite.}}{\mathrm{H_2KAl_3Si_3O_{12}}} + \underset{\textit{Quartz.}}{3\,\mathrm{SiO_2}} + \underset{\textit{Magnetite.}}{\mathrm{Fe_3O_4}}.$$

Stillwell[*] gives the following reaction which may be applicable to the case in which biotite is produced :—

$$\underset{\textit{Garnet.}}{2\,\mathrm{(MgFe)O, CaO, Al_2O_3, 3SiO_2}} + \underset{\textit{Orthoclase.}}{2\,\mathrm{KAlSi_3O_8}} \rightleftarrows \underset{\textit{Biotite.}}{\mathrm{(KH)_2(MgFe)_2Al_2(SiO_4)_3}}$$
$$+ \underset{\textit{Anorthite.}}{\mathrm{CaAl_2Si_2O_8}} + \underset{\textit{Quartz.}}{\mathrm{SiO_2}}.$$

The anorthite molecule is considered to enter into, or be derived from, the composition of the plagioclase which then becomes relatively more basic or more acid according to the direction of the action. It is doubtful whether there is sufficient lime in the garnet to give rise to anorthite in the present case.

Grubenmann[†] illustrates the production of quartz and biotite from garnet and orthoclase by an equation in which sillimanite is produced. The latter mineral does not appear in the present case.

Tilley[‡] interprets the reaction as follows :—

$$\underset{\textit{Biotite.}}{\mathrm{H_4K_2Mg_2Fe_4Al_6(SiO_4)_9}} + \underset{\textit{Quartz.}}{3\,\mathrm{SiO_2}} \rightleftarrows \underset{\textit{Orthoclase.}}{2\,\mathrm{KAlSi_3O_8}} + \underset{\textit{Garnet.}}{2\,\mathrm{Fe_2MgAl_2(SiO_4)_3}} + 2\,\mathrm{H_2O}.$$

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[*] *Op. cit.*, p. 158.

[†] "Die Kristallinen Schiefer." U. Grubenmann. Berlin, Vol. I (1904), p. 52.

[‡] "The Granite-Gneisses of Southern Eyre Peninsula." C. E. Tilley, Q.J.G.S., Vol. lxxvii, Pt. 2 (1921), p. 94.

It was noted that epidote was sometimes developed as a result of the alteration of the garnet. Van Hise * gives the following equation for the development of epidote from a lime-iron-alumina garnet—

$$2\,Ca_3Al_2Si_3O_{12}.\,Ca_3Fe_2Si_3O_{12} + 5\,CO_2 + H_2O = 2\,HCa_2Al_2FeSi_3O_{13} + 5\,CaCO_3 + 3\,SiO_2 + k \text{ (heat liberated)}.$$

In the rocks under discussion, however, calcite is only present in No. 348 where it appears to be derived from calcic plagioclase. In the epidote-magnetite-schist No. 989 and the magnetite-garnet-schist No. 245 epidote is developed from the garnet but there is no free calcite. The above equation therefore represents a garnet with more lime than in the garnets of these rocks.

Van Hise* records that in all cases of alteration of garnet, quartz appears among the secondary minerals. In these rocks magnetite is also as general.

III.—POSITION IN GRUBENMANN'S CLASSIFICATION OF CRYSTALLINE SCHISTS.

The described rocks can be considered in two groups—(1) those in which magnetite is the most important constituent; and (2) those in which garnet and magnetite are equally important.

The members of the first group can be placed in the group of iron oxide rocks (magnetite rocks) which forms Grubenmann's XIth group. The presence of garnet, quartz, plagioclase, orthoclase, biotite, magnetite, &c., and the occurrence of homoblastic and diablastic structures, which are sometimes almost obliterated by later epi structures, all necessitate some form of deep-seated metamorphism. In addition, a transference to epi zone conditions is suggested in some cases by the hydrous minerals associated with the kaolinisation and sericitisation of the felspars and with the development of chlorite and magnetite from garnet and biotite. Thus the magnetite schists and gneisses Nos. 576, 912, 933, 294, and 55 are considered to be epi-meso rock types, but may fall into the family of epi-magnetite rocks of Order III. In Nos. 989, 527A, and 889 the first metamorphism may have resulted from either meso or kata conditions. No. 889, a magnetite-garnet-schist containing cordierite, may be related to the aluminous silicate gneisses (Group II) and the family of kata garnet gneisses. Nos. 765, 926, and 296 appear to be pure meso zone types and belong to Order II, meso magnetite rocks and micaceous hematite schists (Group XI).

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* "Treatise on Metamorphism." C. R. Van Hise. Geol. Surv., U.S.A., monograph 47, 1904, p. 305.

The analysed specimens belong to the second group, and Tables VI and VII give the molecular percentages of the constituent oxides, the group values and the projection values according to Ozann's scheme.*

TABLE VI.

	I.	II.	III.	IV.
SiO_2	56	58·3	61·8	64·4
Al_2O_3	9	11·0	7·6	7·8
FeO	27	21·1	24·8	18·5
CaO	4	2·4	2·2	3·4
MgO	......	3·1	3·5	3·0
K_2O	3	0·6	......	1·1
Na_2O	1	3·5	·1	1·8

TABLE VII.

Group and Projection Values.	I.	II.	III.	IV.	V.
S	56	58·3	61·8	64·4	20·0
A	4	4·1	0·1	2·9	0·0
C	4	2·4	2·2	3·4	0·4
F	27	24·2	28·3	21·5	80·0
M	0	0·0	0·0	0·0	2·5
T	1	4·5	5·3	1·5	0·0
K	0·9	1·1	2·1	1·4	0·3
a	2·2	2·7	·07	2·1	0
c	2·2	1·6	1·4	2·4	0
f	15·6	15·7	18·5	15·5	20

I. No. 149, Magnetite-garnet-gneiss.

II. No. 181, Porphyroblastic magnetite-garnet-gneiss.

III. No. 102, Garnet-quartz-magnetite rock.

IV. No. 348, Garnet-magnetite-schist.

V. Mean values of Grubenmann's XIth Group.

The values for No. 149 have been obtained from the Rosiwal analysis in Table I on the assumption that biotite has the composition $K_2FeAl_2(SiO_4)_3$, that the garnet is almandine and that quartz, orthoclase, and labradorite are present in equal proportions in the rock. The values for the other rocks are obtained directly from the chemical analyses in Table V. The projection values are plotted in the triangular diagram, fig. 1.

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* Grubenmann, *op cit.*, 1910, pp. 134–6.

An examination of the group values of the garnet-magnetite rocks in Table VII shows that these rocks do not fit in any of Grubenmann's groups of crystalline schists. Column 5 gives the mean group values of Group XI, the iron oxide rocks and these show outstanding differences, especially in regard to S and F, with the corresponding values of the garnet-magnetite rocks. Wide as are the variation limits assigned to some groups of the crystalline schists, it appears impossible to include these garnet-magnetite rocks without the creation of a new group. It may, therefore, be advisable to add a new group of garnet magnetite rocks, just as two new groups have been created (1) for certain manganiferous rocks in India. Hezner has added a manganese silicate group which is naturally united to the lime silicate rocks by all its chemical, mineralogical, and genetic relations, and also a new manganese oxide group which best follows the XIth Group of iron oxide rocks.

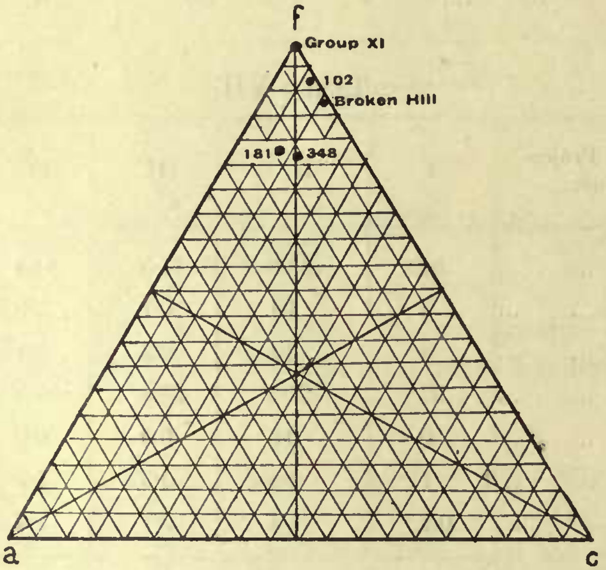

Fig. 1.

Nos. 149, 181, and 348 would be types of a new garnet magnetite rock group, while No. 182 would be somewhat abnormal. The chief minerals of such a group are garnet, magnetite, and quartz. Other minerals which may be present are biotite, felspar, cordierite, sillimanite, and epidote. Ilmenite, rutile, and hematite may be intergrown with magnetite. Kata zone types are represented by Nos. 149, 827, and 304. Meso zone types include Nos. 149, 814, and 245, while Nos. 181, 288, and 348 have apparently been subjected to epi zone metamorphism as well as meso zone metamorphism.

On the other hand, if, as will appear likely, igneous emanations are concerned in the formation of these magnetite garnet gneisses, it becomes doubtful whether any attempt should be made to fit them into Grubenmann's classification of the crystalline schists.

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* "Uber manganreiche Kristalline schiefer Indiens." L. Hezner, Neues Jahrbuch fur Minerologie, &c., 1919, p. 28.

IV.—GENERAL DISCUSSION.

As the specimens are morainic boulders there is no field evidence bearing on the question of their origin. The nature and character of the magnetite-schists Nos. 912 and 294, the quartz-magnetite-schist No. 296, the epidote-magnetite-schist No. 989, the mica-magnetite-schists Nos. 55 and 933, and possibly also the garnet-magnetite-gneiss No. 827 indicate that they very more likely to be derivatives of sedimentary rocks rather than igneous rocks. The probability is not so high in the case of the garnet-magnetite rocks. The evidence of the chemical analyses of the three specimens in Table V is not decisive. There is a considerable excess of alumina over the 1 to 1 ratio with the lime and alkalies and this, combined with the mineral content, suggests derivation from a sediment. On the other hand, CaO is in excess over MgO in two analyses and Na_2O is in excess of K_2O. Less weight is attached to these points and in general it is believed that a sedimentay rather than an igneous origin is to be ascribed to the whole class. Yet the chemical composition is clearly not that of a common sediment.

An interesting comparative occurrence is the quartz-garnet-magnetite-schist from Broken Hill, New South Wales. It occurs* in the neighbourhood of the Broken Hill lode in discontinuous lenses along bands which dip conformably with the associated garnet-sillimanite-gneisses. A specimen from a locality, one mile south of Menindie-road, 4 miles south of Broken Hill, has been studied. It is a schistose rock composed of magnetite, garnet, quartz, and apatite in the proportions given in Table I. It may be noted that the proportions of iron ore to garnet are approximately the reverse of that in No. 102, its nearest relative among the Cape Denison specimens. While No. 102, with 2 per cent. of apatite, is comparatively rich in phosphorus, this is greatly exceeded by the Broken Hill specimen with 14·2 per cent. of apatite.

The chemical analysis of the Broken Hill type is quoted in Table V, and the negligible alkalies, the low magnesia, and high iron are strong points of resemblance. The differences in silica percentages correspond with differences in the amount of quartz. The percentages of lime and phosphorus are much higher than those in No. 102. corresponding to the abundant apatite. The Broken Hill type contains 7·08 per cent. of manganese and is comparable with the 8·23 per cent. in No. 348, where the garnets are manganiferous.

There are thus striking resemblances between the Broken Hill type and the garnet-magnetite specimens from Cape Denison. The Broken Hill type is described by Andrews† as a lode formed from emanations given off, apparently at a depth, from igneous material along a crush zone, and further formed by replacement. He points out (p. 174) that the garnet-magnetite type is associated with garnet-sillimanite rocks, while the quartz-magnetite types, without garnet, are associated with mica schists. Browne‡ believes these rocks to be pegmatitic derivatives of the gabbro magma which are intruded as a metasomatic replacement of a zone of country rock. Further, these authors appear to regard the garnet as a primary igneous mineral.

---

* "Geology of Broken Hill." E. C. Andrews. Mem. 8, Geol. Surv. N.S.W., 1923, p. 171.

† "Geology of Broken Hill District." E. C. Andrews, Geol. Surv. N.S.W., No. 8, 1922, p. 181.

‡ Appendix I of "Geology of Broken Hill District." W. E. Browne, p. 340.

The comparison with the Broken Hill occurrence should therefore imply that the garnet-magnetite rocks are derived from an igneous source.

Another related group of rocks are the " Skarn " rocks of Norway and Sweden. Skarn* is an old Swedish mining term for the sillicate gangue of certain iron ore and sulphide deposits of Archaean age. Its use has been extended by Goldschmidt† to all lime-iron-silicate rocks which arise through the contact metamorphism of limestone, including andradite rocks, hedenbergite rocks and andradite-hedenbergite rocks. The iron ore of the skarn rocks (including garnet-magnetite rocks) is arranged in layers parallel to the schistosity or bedding. Goldschmidt is sceptical of the view that such rocks are magmatic differentiation products—a view adopted by Browne for the Broken Hill type. Goldschmidt considers them to be pneumatolytic contact rocks determined by three factors, (1) pneumatolytic action in depth, (2) presence of a limestone, and (3) absorption and enrichment of the constituents of the magmatic gases.

The skarn formation from limestone takes place through increase of silica and iron. It is supposed that iron chloride is introduced in gaseous form along joints and fissures with the result

$$2\ FeCl_3 + 3\ CaCO_3 = Fe_2O_3 + 3\ CaCl_2 + 3\ CO_2.$$

In this way the limestone collects the iron from the issuing magmatic gases. The silicon is probably introduced as a halogen compound which reacts with the calcite to form quartz. Quartz then combines with calcite forming wollastonite which, when there is sufficient iron oxide, combines to form andradite.

$$\underset{\textit{Wollastonite.}}{3\ CaSiO_3} + Fe_2O_3 = \underset{\textit{Andratite.}}{Ca_3Fe_2Si_3O_{12}}.$$

Manganese, which is a notable component of many skarn rocks, is introduced in the same way as the iron.

$$MnCl_2 + CaCO_3 = MnO + CaCl_2 + CO_2.$$

The MnO, however, generally enters the silicate.

Goldschmidt thus considers that the skarn rocks are the result of metasomatic pneumatolytic processes acting on limestones, and their unusual composition is explained by the acquisition of material from the magmatic source.

Somewhat similar rocks at Morenci, Arizona, are considered by Lindgren‡ to have been derived from limestones by the addition of large amounts of ferric oxide and silica.

---

* " Nomenclature of Petrology." A. Holmes. London, 1920, p. 211.

† " Die Kontaktmetamorphose im Kristianiagebiet." V. M. Goldschmidt, Christiania, 1911, p. 211 et seq.

‡ " The Copper Deposits of the Clifton-Morenci District, Arizona." W. Lindgren, U.S. Geol. Surv., Prof. pap. 43, 1905, p. 160.

In the Broken Hill occurrence no associated limestone is reported, neither does the garnet of the Adelie Land specimens correspond to andradite. Yet it is interesting to note that the same moraines have yielded a number of specimens of metamorphic limestones and calc-silicates rocks.* It is known, however, that similar garnet rocks can be produced without limestone. Kemp,† in commenting on the processes of garnet formation in contact rocks of intrusive zones, concludes that, where limestone is absent, the emissions from the deeper parts of the eruptive supplies the lime and iron oxide for the garnet occurrences in such rocks as quartzites, schist, and gneiss, just as the reverse contributions of silica and iron and alumina to the limestone would lead to the same result. In the Broken Hill type it is clear that there has also been an important addition of phosphorus.

In the garnet-magnetite types from Cape Denison the garnet is a variety containing magnesium, iron, manganese, and alumina. Felspar, as noted above, is often an important constituent though it fails in the quartz-garnet-magnetite rock, No. 102. The presence of aluminous garnet in addition to felspar suggests that the garnet-magnetite formation has occurred in a rock in which there has been sufficient alumina and silica to satisfy all the alkalies and available lime for the formation of felspar, and further that the garnet-magnetite formation has occurred in the presence of excess alumina rather than excess lime. Where P_2O_5 is present or introduced, the lime would be incorporated in apatite in preference to felspar. Aluminous garnet is present in the analogous type at Broken Hill which occurs in a sedimentary series with excess alumina, expressed in abundant sillimanite. It is therefore possible that the Cape Denison types have developed in aluminous sediments similar to those which are related to the magnetite schists, Nos. 912 and 294, and the related types Nos. 296, 989 and 933.

In conclusion, it is therefore likely that the garnet-magnetite rocks of Cape Denison have resulted from the metamorphism of sediments, the composition of which has been modified by igneous emanations.

V.—TOURMALINE-BEARING MAGNETITE GNEISS.

In view of the probable role of igneous emanations in the formation of the garnet-magnetite rocks the following description of No. 252, a tourmaline-bearing and garnet-free type, has added interest.

No. 252 is a banded variety, in general fine grained, but with coarsely crystalline bands of quartz and bluish cordierite. Tourmaline is very abundant and long needles of sillimanite and black grains of magnetite are plainly seen in the hand specimen. The proportions of cordierite, magnetite, tourmaline and sillmanite are very variable. The specific gravity of the rock is 3·09.

---

* "The Metamorphic Limestones of Commonwealth Bay, Adelie Land." C. E. Tilley. Aust. Ant. Exp. Sci. Rpts. Series A., vol. iii, pt. II, pp. 231–243.

† "Ore Deposits at the Contacts of Intrusive Rocks and Limestones." J. F. Kemp. Journ. Geol., vol. ii, pp. 1–13.

A portion of the rock, which was very rich in tourmaline, was sectioned in a direction at right angles to the schistosity. A Rosiwal analysis resulted in the following :

Quartz, cordierite, and sillimanite	47·5
Tourmaline	30·1
Magnetite	21·4
Apatite	1·0

The tourmaline is a strongly pleochroic variety, changing from green to a reddish- or brownish-violet. The flakes show a rather infrequent cleavage and contain gas, magnetite, and minute zircon or monazite inclusions, sometimes with a definite alignment. Where these minute zircons or monazites are present, there is occasionally a distinct lightening of colour in the form of a halo around the inclusion. The colours of the tourmaline sometimes vary locally in a zonal fashion. The mineral is associated with magnetite, both occurring in bands throughout the rock.

Cordierite is abundant and exhibits a great number of well-formed pleochroic halos around inclusions of either zircon or monazite (Plate II, fig. 6.) While the experience of Joly and Fletcher* has indicated that halos in cordierite cannot be used for accurate measurement, the halos in this rock are remarkably distinct and capable of measurement. By means of a Beck micrometer eye-piece and a 4 mm. (x 45) objective, the following results were obtained, the radii given being always the distance from the outer edge of the halo to the edge of the inclusion. All measurements are in millimetres.

TABLE VIII.

No.	Radius of Halo.	Remarks.	Dimensions of Nucleus.	Remarks.
1	·041	Distinct	·020 x ·020	Circular.
2	·041	Perfect halo, very distinct	·031 x ·022	Oval, oblique extinction.
3	·040	Distinct	·054 x ·030	Oval, oblique extinction.
4	·040	Indistinct, passing through both cordierite and sillimanite.	·023 x ·017	Prismatic, oblique extinction. Zircon.
5	·040	Indistinct, passing through both cordierite and sillimanite.	·054 x ·018	Prismatic, oblique extinction.
6	·040	Very distinct, lighter in colour for about ·020 mm. from the inclusion.	·032 x ·028	Oval, oblique extinction.
7	·040	Indistinct, fainter near nucleus for about ·012 mm.	·033 x ·029	....
8	Large......	Indistinct	·083 x ·027	Zircon.
9	·026	Fairly distinct, passing through sillimanite and cordierite.	·038 x ·015	Oval, oblique extinction.
10	·021	Indistinct	·015 x ·010	Oval, oblique extinction.
11	·020	Fairly distinct	·017 x ·011	Oval, oblique extinction.
12	·020	Indistinct, faint at sides	·016 x ·011	Oval.
13	·016	Doubtful	....	....
14	·015	Fairly distinct	·010 x ·008	Straight extinction.
15	......	Indistinct	·038 x ·027	Wedge shaped.

---

* "Pleochroic Halo." Phil. Mag., 6th series, vol. xix, 1910, p. 635.

As in the halos measured in No. 149 in biotite, corona effects are generally absent, being noted only in two cases, and Joly's correction for nuclei, based on the assumption that they are zircon and sensibly spherical, obviously cannot be made. By a comparison with the list of radii given by Joly and Fletcher, it seems probable, as the dimensions of the halos in cordierite will not differ markedly from those in biotite, that No. 1–8 owe their origin to Th C, No. 9 to Th X and Nos. 10–12 to Ra A.

The cordierite is much intergrown with long prismatic needles of sillimanite which make the measurement of halos sometimes very difficult. In places the halos are so numerous that the cordierite remains brown throughout a complete revolution of the stage. As has been noted above, the radioactive inclusions are not confined to cordierite, some occurring in tourmaline. Monazite appears to be the more common nucleus in No. 252, while zircon was the more frequent in No. 149. The cordierite is at times altered to a yellowish-brown form of biotite and at others the change proceeds, from a centre, giving a chloritic mass.

Quartz is abundant and distinguished from cordierite by the absence of halos cleavage and decomposition. Apatite is frequent but it is restricted to certain bands in which it is associated with magnetite. The structure of the rock is homoblastic, and though the nature of the different bands is very variable a general name would be *Tourmaline-Magnetite-Sillimanite-Cordierite-Gneiss.*

The absence of felspars and the abundance of sillimanite and cordierite clearly indicate that the rock has been derived from a sediment. The abundance of tourmaline indicates the action of igneous emanations and tends to confirm the similar view in regard to magnetite and apatite.

In Grubenmann's classification it would occupy a position in the Kata division of the group of aluminous silicate gneisses (Group II). Within this division there is a family of the sillimanite gneisses and the family of the cordierite gneisses, but the Cape Denison rock is clearly distinct from typical members of these families in the presence of abundant tourmaline and magnetite.

VI.—GENERAL SUMMARY AND ACKNOWLEDGMENTS.

In all twenty-two specimens have been described from Adelie Land and treated as crystalline schists. Two contain abundant magnetite and no garnet. Seven contain dominating magnetite and, together with the preceding two, are associated with the iron oxide group, No. XI, of Grubenmann's classification of the crystalline schists. In ten specimens garnet is approximately as important as the magnetite. The chemical characters of these types are widely different from any defined group of crystalline schists and a new group of garnet-magnetite rocks is suggested.

The types are probably derived from sediments whose composition has been modified by igneous emanations. Such origin is rendered the more likely by the final type which is rich in tourmaline as well as magnetite.

Measurements of pleochroic halos and nuclei have been made in both cordierite and biotite. The formation of these halos has been ascribed partly to Th C, partly to Th X and Ra A.

In conclusion, the writer desires to thank Professor W. W. Watts, of the Royal School of Mines, South Kensington, for kind assistance in the prosecution of research, and he is also specially indebted to Dr. F. L. Stillwell, at whose suggestion the work was undertaken and who has given the writer every possible assistance and unhesitatingly helped with his great experience of Adelie Land specimens.

VII.—DESCRIPTION OF PLATES.

PLATE I.

Fig. 1.—No. 181, Porphyroblastic-Magnetite-Garnet-Gneiss. Photo, F. L. Stillwell. Note that the scale photographed with the specimen in this plate is graduated in inches.

Fig. 2.—No. 650, Porphyroblastic-Magnetite-Garnet-Schist, with a well-defined "linear" structure. Photo, F. L. Stillwell.

PLATE II.

Fig. 1.—No. 527A, Chlorite-Magnetite-Schist, showing the alteration of garnet into a mass of quartz, magnetite, and chlorite with residual garnet. Mag. 113 diams. Photo, G. S. Sweeting.

Fig. 2.—Siliceous vein crossing the Micaceous-Magnetite-Schist, No. 933. The dark central area in the vein is felspar. Mag. 22 diams. crossed nicols. Photo, G. S. Sweeting.

Fig. 3.—No. 889, Magnetite-Garnet-Schist, showing parallel line development with garnet. Mag. 25 diams. Photo, G. S. Sweeting.

Fig. 4.—Magnetite-Garnet-Gneiss, No. 149, containing pleochroic halos around radioactive inclusions in biotite. Mag. 48 diams. Photo, G. S. Sweeting.

Fig. 5.—No. 102, a rock composed of garnet, quartz, magnetite, and apatite. Mag. 24 diams. Photo, G. S. Sweeting.

Fig. 6.—No. 252, Tourmaline-Magnetite-Gneiss, with numerous perfect pleochroic halos in cordierite. Tourmaline (dark with cross cleavage), sillimanite (fibrous) and magnetite (black) can also be seen. Mag. 34 diam. Photo, G. S. Sweeting.

[Two plates.]

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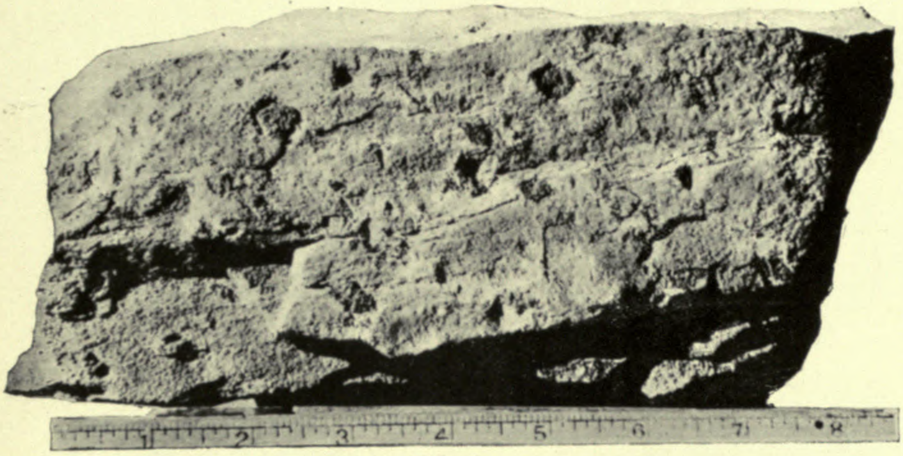

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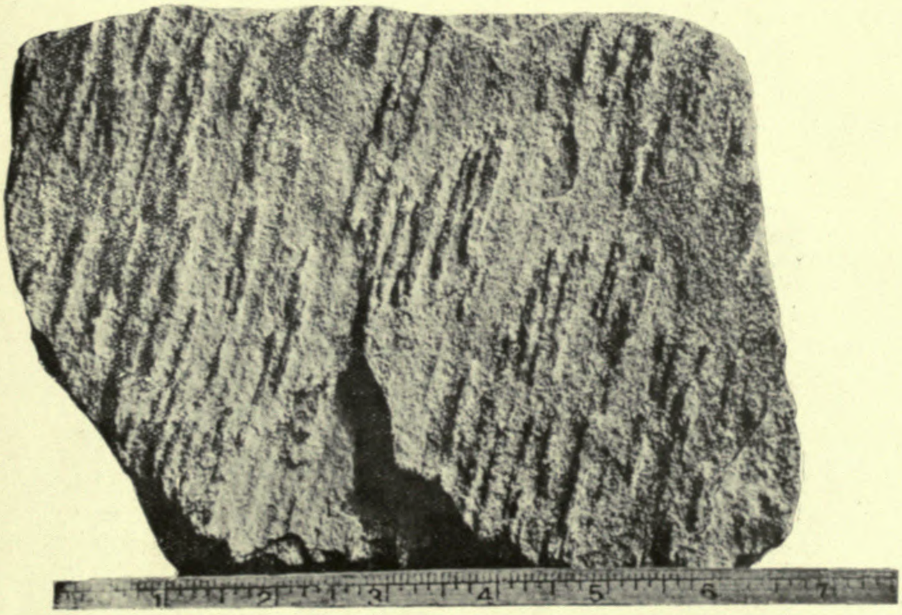

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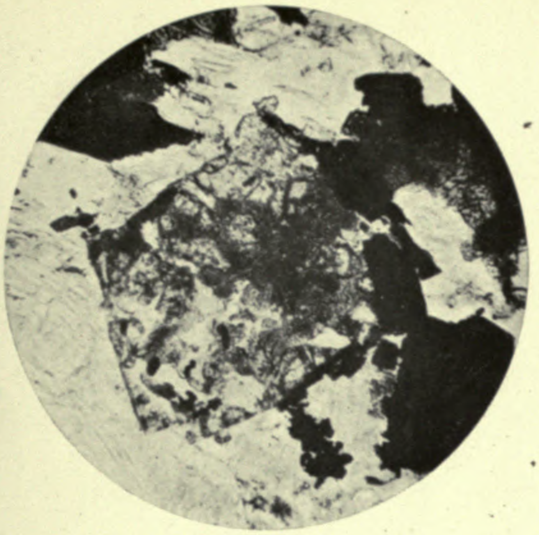

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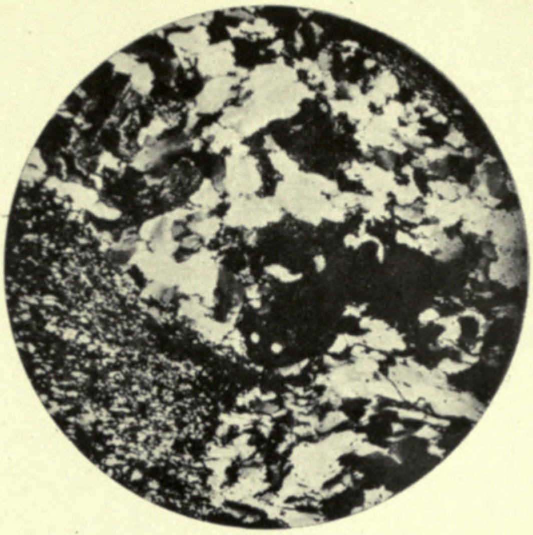

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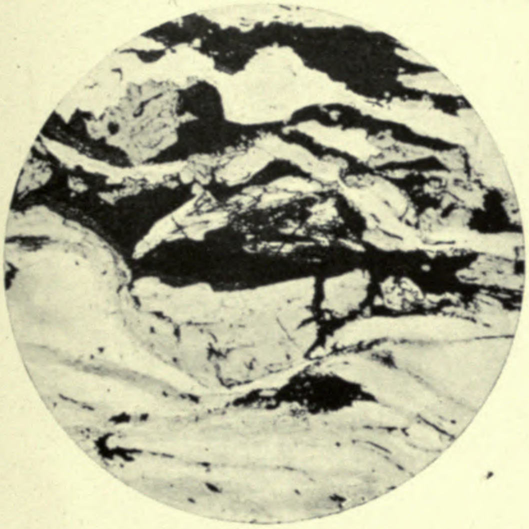

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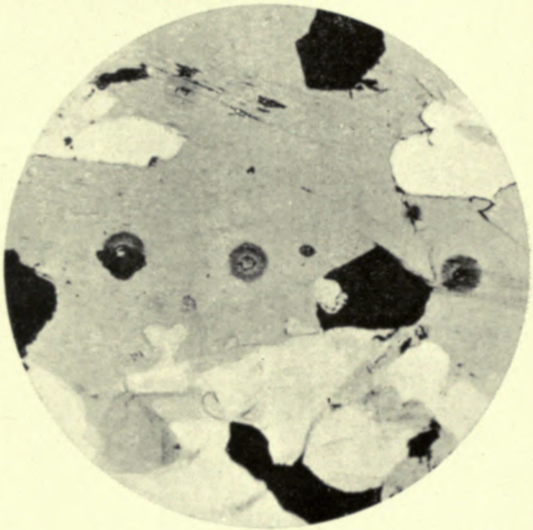

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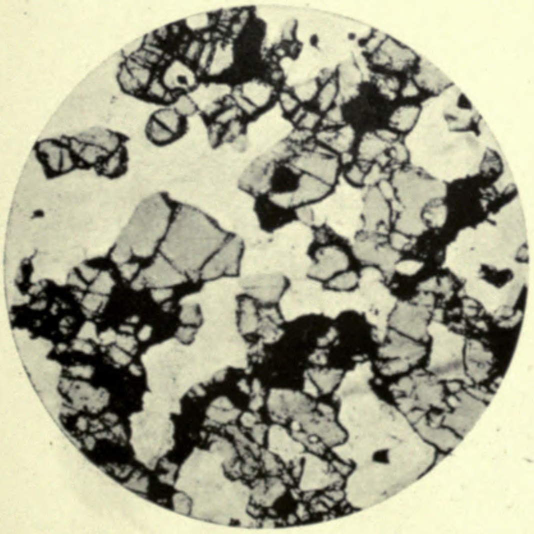

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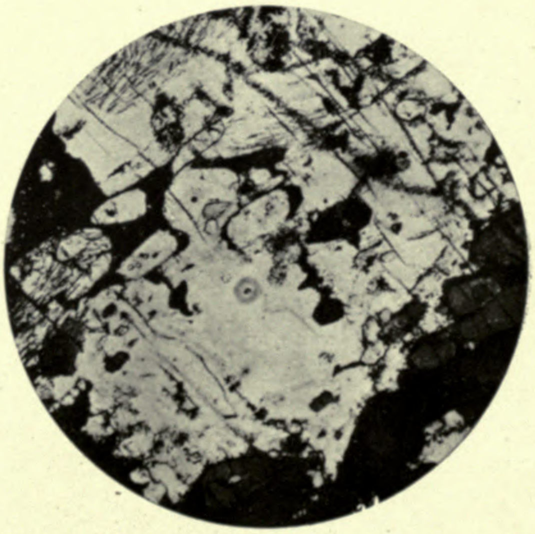

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I. NOTES ON FURTHER* SPECIMENS FROM THE METAMORPHOSED DYKE SERIES OF CAPE DENISON.

1. INTRODUCTION.

" ONE band of amphibolite, outcropping near the centre of the Cape Denison area, is phenomenal in containing a large number of xenoliths. There are two distinct types of material among these meta-xenoliths, and they may be distinguished as—

(1) Saussuritic type;

(2) Gneissic type.

The saussuritic type includes pale green and pale pink masses which may be again subdivided into—

(*a*) Those composed wholly of saussurite—the individual type.

(*b*) Those composed of an aggregate of saussurite and hornblende—the composite type." (Stillwell: Series A, Vol. III, Pt. 1, p. 48.)

This statement of Stillwell's is given because the rocks to be discussed here (Nos. 142, 421, 432, 632, 633, 635A, 666 and 1240) are all members of the dark amphibolitic series found *in situ* at Cape Denison.

No. 421 is the coarsest of the set. As seen in the hand specimen it consists of handsome blades of black hornblende set in a base of coarsely crystalline opaque felspar. Its structure is gneissic.

Nos. 432, 666 and 1240 are examples of the amphibolite xenoliths containing porphyritic saussurite individuals. They are of " The individual type of meta-xenolith " variety according to Stillwell's classification.

No. 142 is another of the individual type of meta-xenolith, but owing to the few phenocrysts of saussurite and the definite schistosity it has taken up it seemed well to give it a further description.

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*Dr. Stillwell's original report deals with outstanding examples of the dominant types of rocks met with *in situ*. Rocks described in this contribution are, in the main, closely similar to examples selected and described by Stillwell. The present descriptions are supplied in order to render more complete the microscopical examination of the whole of the rock collection. D.M.

Nos. 632, 633 and 635A are specimens of amphibolites from the metamorphosed dyke series of Cape Denison. These specimens are like Nos. 634, 634A and 635 described by Stillwell in this connection. They have developed schistosity to a considerable degree by a parallel arrangement of hornblende prisms. Both Nos. 632 and 633 are markedly fissile because of the perfection of this parallelism.

2. Mineralogical Characters of the Individual Xenoliths.

Under the microscope Nos. 142, 421, and 431 fall into one mineralogical division and Nos. 666 and 1240 in another. The differences are not so much in actual mineral content as in the nature of the crystal development. In the first three of these rocks the felspar, not only in the phenocrysts themselves, but throughout the whole rock-mass is turbid and highly saussuritised. The amphibole present is pale green in colour and is definitely actinolitic in character. The crystals are elongated but small. They have not the massive, compact appearance of typical hornblende. Their colour, as a matter of fact, tends to blue, suggesting that the glaucophane molecule has been concentrated in them to some extent. No. 666 serves as a transition stage. It is marked by the plagioclase intermingled with the amphibole crystals, as distinct from that in the saussurite phenocrysts, being pellucid. This shows that the felspar of these regions has completely recrystallised and either assumed again the matter rejected during saussuritisation or expelled it by diffusion to be taken up in the composition of the hornblende. The amphibole in this rock is not so actinolitic as in the first three, but it is by no means so compact and green as in rock No. 1240.

In this rock, No. 1240, the chief difference from the others mentioned above, is the intense green and brownish green colour of the amphibole, which now is quite definitely hornblende. Another striking difference is the almost entire absence of saussurite which is present in the nuclei of two large phenocrysts only.

Other mineralogical points of interest are first, the relationship of sphene and nuclear ilmenite. The development of this is shown quite well in these rocks. In No. 142 the border of the sphene is quite narrow, sometimes less than 0·005 mm., while in the other rocks there is a range of 0·05 mm., and perhaps even more. Secondly, a genetical relationship between the three minerals ilmenite, sphene and zoisite (or clino-zoisite, or epidote as the case may be) and felspar is shown by a similar serial arrangement.

Other reactions which involve sphene are best seen in Nos. 142 and 421. In these rocks a more fibrous biotite than usual, whose pleochroism is from Z a weak brown to X practically colourless, is found associated with grains of sphene, hornblende and nearly colourless chlorite (Plate XLV, fig. 1). The chlorite is derived from the biotite, its development being a possible explanation of the bleaching of the colour of the mica. The sphene seems to be forming chiefly at the expense of the hornblende which, as a result, is poikiloblastic in texture and studded with small inclusions of the sphene. But a similar relation exists, to a more limited extent, between the biotite and sphene.

This is more particularly noticeable where biotite and hornblende crystals interlock, that is, where it is more definite that the two minerals were formed by the same general alteration of the augite of the dolerite rocks. Epidote, too, is associated with this brown biotite, but is a rim-growth rather than an inclusion.

The minerals epidote, zoisite, clino-zoisite are usually found with white mica in the saussurite matrix. The lawsonite, however, is not so restricted as the others; it occurs (in addition to the above manner) as veins which penetrate the amphibole masses and in localised patches in the neighbourhood of the amphibole. Frequently zoisite is found as irregular scales which thread through the saussurite. Under crossed-nicols it is seen to form an ultra-blue background in which the other alteration minerals and relic felspar occur.

In Nos. 666 and 1240, there is practically no sphene, and no biotite or chlorite. This shows that when the more complex amphiboles are produced in the higher stages of metamorphism they have absorbed into their composition much of the matter of both sphene and biotite. The disappearance of white mica, epidote and zoisite, and the recrystallisation of the felspar in a more acidic form emphasise the increased complexity of the new amphibole molecule; and this variation in chemical content is reflected in the different appearance of the mineral.

3. Genesis of the Xenoliths.

This has been discussed by Stillwell on pp. 53–54 of his work. He immediately (pp. 54–5) proceeds adequately to discuss the significance of the meta-xenoliths. In view of this, nothing further will be given here on these matters.

4. The Amphibolites of the Metamorphosed Dyke Series.

This account is concerned with the mineral composition and the microscopical characters of the amphibolite rocks Nos. 632, 633 and 635A.

No. 632 differs from No. 633 under the microscope. Although it shows some tendency to linearity of amphibole crystal arrangement, yet, on the whole, it is advisable to call its texture granoblastic. In No. 633, however, there is a marked schistosity produced by the parallel orientation of its amphibole crystals. This schistosity is accentuated by the elongation of the crystal prisms whose average elongation factor (length : width) is about 3; this is exceeded somewhat in regions where smaller crystals are interwoven with felspar; it is fallen short of in the more massive parts of the rock. Again, in No. 632, there is a fairly even distribution of parts exclusively amphibolic and parts essentially composed of both amphibole and felspar. No. 633, on the other hand, has these mineral groups arranged in parallel alignment, producing a completely different aspect.

The minerals present in these two rocks are much alike. The dominant one is a pale blue-green actinolite. This is sometimes concentrated in zones free from other minerals, and sometimes associated with highly saussuritised felspar. The saussuritic mass contains epidote, zoisite and clino-zoisite. No. 632 contains an occasional lath of biotite, but this mica, as an unusually pale variety, is one of the determinative minerals of the finer-grained regions of No. 633. Each rock contains some granules of sphene, rare grains of ilmenite and crystals of apatite.

No. 635A is a rock in which the simpler pale-green actinolite has been recrystallised into more complex green amphibole. This recrystallisation of amphibole has been accompanied (or preceeded) by a recrystallisation of felspar. The hornblende crystals are small, but no longer exclusively elongated, as a matter of fact they are usually equi-dimensional. They do not exhibit such marked parallelism as do the crystals of amphibole in No. 633. Sphene has practically disappeared, the biotite has a much stronger reddish brown colour. These facts, together with the deeper green colour of the amphibole, again emphasise the way in which the amphibole (and the mica too) gain complexity in the higher grades of metamorphism by the absorption of the "rejection products" of saussuritisation and of minerals like sphene. Lawsonite and the suite of epidote minerals are practically absent.

The recrystallisation of the felspar has resulted in the formation of many grains of quartz. The new felspar is frequently twinned, both albite and pericline multiple twin lamellae being seen.

Some little iron ore (magnetite) and rods and needles of apatite are also present.

These three rock types can be summarised thus :—

No. 632—Chlorite-albite-epidote-amphibolite.

No. 633—Chlorite-albite-epidote-amphibolite-schist.

No. 635A—Amphibolite.

II. NOTES ON ADDITIONAL ROCK TYPES FROM STILLWELL ISLAND.

1. Introduction.

A discussion of some of the rock types found at Stillwell Island has already been given in these Scientific Reports (Stillwell, Vol. III, Pt. 1). A brief résumé of some of the points made there is necessary for an understanding of the sequel.

"Stillwell Island is one of the largest members of the Way Archipelago.

The most conspicuous rock is a massive granitoid gneiss, often carrying abundant dark aggregates of garnet and mica. Varieties of gneiss are also found without any garnet at all, and the higher part of the island is formed of an acid hypersthene gneiss.

In crossing the islet areas are found consisting of more strongly foliated gneisses, and the trend of the foliation is a little west and north. Irregular bands of black gneiss, with dyke form, exist here as at Cape Denison, and some are full of fine garnet." (pp. 145–6.)

Mention is then made of—

(*a*) Garnet gneisses (No. 917), p. 151;
(*b*) Acid hypersthene gneisses (Nos. 979, 947), p. 155;
(*c*) Metamorphosed basic dyke series (Nos. 951, 942, 935, 953, 952), p. 171.

The present contribution is devoted to a further description of these groups with mention of specimens not dealt with by Dr. Stillwell, but which show variations from the main types and important differences in detail.

The specimens dealt with are Nos. 59, 699, 972, 973, 974, 976, 977, 978, 980.

It is found that Nos. 699 and 980 fall in Group (*a*), the Garnet Gneisses, and Nos. 591, 972, 973, 974, 976, 977 and 978 are all members of the metamorphosed basic dyke series, Group (*c*).

2. PETROGRAPHY.

(a) *The Garnet Gneisses.*

As mentioned above the additional members to this group of gneisses which occur both at Cape Pigeon Rocks and Stillwell Island are Nos. 699 and 980.

No. 699. Garnet-Felspar-Quartz-Gneiss.

This rock consists of alternate bands of biotite and quartz-felspar matter. Through the rock, but concentrated to a greater extent in the vicinity of the biotite, are clusters of deep red garnet crystals, some of which assume a high degree of crystalline form.

In some respects this rock resembles Nos. 777 and 917 described by Stillwell. The former was collected at Garnet Point and the latter at Stillwell Island. There are large porphyroblasts of garnet, and although they are to some extent penetrated by biotite, they are not skeletal like those of No. 777. The mica developed is of two kinds. One is biotite which is found as a greenish-yellow fibrous mass forming an aureole around the garnet, and as more compact masses pleochroic in dark and light browns. The other mica is sericite which has developed during the alteration of potassic felspar.

The areas not so immediately associated with the garnet consist of quartz, plagioclase, orthoclase, microcline, microcline-microperthite, sericite, calcite and accessory apatite.

The quartz is frequently undulose and contains inclusions of fluorite arranged in long parallel lines. The fact that the fluorite shows abnormal birefringence is evidence that the mineral has suffered internal tension. The quartz and orthoclase frequently occur in a myrmekitic intergrowth; other varieties of intergrowth occur, of which the commonest consists of blebs of quartz included in areas of orthoclase. The felspar, when plagioclase, is very highly saussuritised. Some lamellar twin forms, both albite and pericline, are present. The orthoclase and microcline are, in part at least, developments due to the concentration of the potassium from earlier plagioclase which must have been highly potassic. A further development has been the production of considerable sericite which is almost invariably associated with secondary calcite, the mineral which has been formed by the contemporaneous concentration of the lime molecule of the original felspar. The existence of quartz and calcite together is evidence of the dynamothermal metamorphism to which the rock has been subjected.

Zircon occurs as nuclei of intense pleochroic haloes in the biotite and also as isolated fragments in the orthoclase. Its brown colour is suggestive of monazite, but its positive uniaxial nature differentiates it from that mineral.

The structures developed are porphyroblastic, shown by the garnet, granoblastic shown by almost the whole of the remainder of the rock, and granulitic shown by the calcite.

No. 59. Garnet-Plagioclase-Pyroxene-Hornblende Gneiss.

A note with this specimen made at the time of collection (by Dr. Mawson) records that it forms a broad band about 20 feet wide with ill-defined borders where the boat was kellicked when a landing was made upon the island.

The rock itself is gneissic. It is composed of black pyroxene and amphibole crystals set in a mesh-work structure of brown matter, whose content is made up of pink garnet, felspar and a very little quartz.

The mineral content of the rock is pyroxene, hornblende, biotite, ilmenite, garnet, andesine, quartz and pyrites.

The pyroxene is non-pleochroic. It always shows some indication of alteration. There is exhibited a serial change in different parts of the rock. The simplest is the separation of ilmenite as fine dust particles which make the mineral very dark and patchy. There is usually, but not always, an accompanying development of green hornblende; particularly is this true in the peripheral areas where a border of hornblende round the pyroxene is quite common. This last development sometimes occurs with grains of quartz (or very acid felspar), thus showing that these two constituents have been formed contemporaneously by the mineralogical alteration of the pyroxene.

The rest of the mineralogical changes are of interest for they show the progressive stages in the formation of garnet by the interaction of felspar and hornblende—as a variation there is also seen the formation of garnet from the reaction between biotite and felspar. The usual arrangement of these minerals consists of a central core of skeletal ilmenite interwoven with brown biotite which gives way to a surrounding zone of hornblende—the ilmenitiferous content is much lower—and the hornblende, in turn, frequently terminates in phalanges which project into reaction areas of highly acidic felspar or quartz. These reaction areas are usually found as inner zones next to the zone of garnet. They show how the amphibole and the original basic felspar combine to form the garnet and to give rise to a separation of quartz. That this separation of quartz is an intermediate stage of the metamorphism and not the final one, is made evident where garnet and the green hornblende abut without an accompanying acidic reaction zone. The acidic material set free in the earlier reaction has been taken up completely in the final one and hornblende and garnet are, in consequence, in intimate juxtaposition.

Exactly similar relationships are seen to hold wherever the biotite region has been able to react with the original felspar. There are places where phalanges of biotite mingle with clear siliceous matter (or highly siliceous felspar), and there are other places where the biotite and garnet abut against one another. This is good evidence of the complementary nature of the biotite and the hornblende; the one being the more ilmenitic derivative of the original pyroxene and the other the component richer in iron and more especially magnesia. They show, too, how the original pyroxene has progressively altered, first, setting free a swarm of ilmenite grains; secondly, producing a granulitic pyroxenic aggregate; thirdly, the formation of green hornblende; fourthly, the subsidiary production of brown biotite by the concentration of ilmenite in the ferromagnesian, and lastly the reaction between the new ferromagnesian and the original basic felspar with the final production of a pink garnet but with the intermediate stage of silica liberation and later phase of absorption of this matter.

Some indication of the structure of the rock has been given by what has been said above. But the general arrangement of the mineral masses is that these more or less circular masses are set somewhat regularly in a felspathic base. In places two or more ferromagnesian alteration zones have coalesced and then the same internal structures are seen to be preserved but there is now no separation region of felspar. The circular nature of the pyroxene and its derivative minerals sometimes gives place to an elongated formation—probably due to the effects of non-hydrostatic stresses—where the length and breadth of the masses are roughly in the ratio 2 : 1. Where the pyroxene is not much altered the average grain-size is about 0·55 mm. This size is preserved remarkably consistently throughout all the metamorphic stages, and finally there has been produced a core of ilmenite, biotite, and hornblende about 0·5 mm. across with a surrounding aureole of garnet from 0·05 mm. to 0·10 mm. wide. The distance between the adjacent nuclei of these masses is about 0·8 mm., leaving an average space of 0·10 mm. to 0·15 mm. occupied by the felspar.

No. 980. A coarse Garnet-Plagioclase-Cordierite-Biotite Gneiss.

A coarse-grained garnetiferous rock was collected from the summit of Stillwell Island. The perfectly developed garnet crystals are set in a matrix of dense greyish felspar. A contact region is present in the specimen examined, where a considerable quantity of biotite comes into the rock and where the grain-size is much reduced.

Regional metamorphism has been the chief determinative factor in the constitution of this rock. The high temperature-pressure conditions which prevailed were followed by thermal metamorphism where pressure no longer was one of the dominant factors operating. This throws new light on the metamorphic transformations which have taken place in the rocks of the island.

The large garnet crystals which dominate the slide have been formed under the first set of conditions mentioned above; but the masses of strongly coloured brown biotite and little accompanying flaky chlorite scattered throughout their whole mass are more likely products of the second set of circumstances. As is true in the case of the red garnets of the Scottish Highlands (Harker, p. 324), so here the formation of biotite which has assumed a decussate arrangement in some places and rosette forms in others has from the garnet liberated ilmenite, which is seen in skeletal crystals, and some interstitial cordierite which, though clear, is usually intensely crushed. The cordierite is recognised by the presence of intensely pleochroic yellow haloes and its biaxial nature (2V large, approximately 80°). The alteration of the chemical nature of the minerals of the rock has proceeded, *pari passu*, with the disintegration of the crystal form. Smaller, more or less skeletal, masses of garnet are separated from one another by the products of alteration, ilmenite, cordierite and biotite.

The pleochroism of the biotite (apparently titania-rich) is intense, the colours being Z deep red-brown, and X very pale brown. The absorption as usual is $Z > X$. Other features of the biotite are the presence of numerous pleochroic haloes with zircon nuclei and the bent nature of the laminae. The bending shows that a shear stress has been operative to a perceptible degree.

In the coarser parts of the rock the acidic plagioclase present occurs in large grains which, however, have been considerably crushed, but more especially is this noticeable in the neighbourhood of the biotite and the garnet. The plagioclase is not so clear in this rock as in most rocks from this area, nevertheless it shows albite and pericline twins very well developed. Bends in the twin lamellae are further evidence that shear has occurred in the history of the rock. Quartz grains are associated with the plagioclase, particularly in the parts where granulitisation has been most intense.

In the finer parts of the rock practically no garnet is seen at all. In its stead is a granulitic aggregate of cordierite and clear acid felspar shot through with flakes of brown biotite and scales of very green chlorite. The disintegration which is noticeable in the very large garnet crystals of the coarser part of the rock has been able completely to change the nature of the smaller garnets and this mass of cordierite, acid plagioclase, biotite and chlorite, maintaining the position and size of the earlier garnet, is paramorphous after the garnet. The granular nature of the aggregates is realised more clearly under crossed nicols, for then the heterogeneously oriented granules of cordierite form a definite mosaic.

Except for an inevitable difference in size the plagioclase of the finer parts of the rock is much the same as that found in the coarser.

(b) *The Acid Hypersthene Gneisses.*

This division recorded by Stillwell is unrepresented among the present series of specimens.

(c) *The Metamorphosed Dyke Series.*

Sir Douglas Mawson recorded in his diary (p. 171 of present series), "irregular bands of black rock exist as at Cape Denison: some are not much altered, and others are full of fine garnet."

Dr. Stillwell then continues to note that some of the rocks exhibit "remarkable stages of incipient alteration." An alternative hypothesis seems to be suggested by the more recent work of Harker and Wiseman in connection with the so-called epidiorites of the Scottish Highlands: that these rocks are high grade metamorphic types, where hornblende is giving place to two pyroxenes, garnet is developing and granulitic texture is characteristic.

No. 972. Hornblende-Plagioclase-Pyroxene Gneiss.

This is a dense, fine-grained rock. Its apparent uniformity is resolved on close inspection into dark masses of relatively coarser material and dark spots whose grain-size is considerably smaller. An ill-defined band where biotite and quartz are megascopically visible also tends to relieve the uniform nature of the rock.

The biotite and hornblende are not without signs of alteration. The grains of these minerals are arranged in the typical decussate manner, but particularly in the case of the hornblende, instead of being compact they are definitely poikiloblastic due to a development of quartz. Associated with the biotite and hornblende, but more particularly with the biotite, are diablastic and myrmekitic intergrowths of quartz and orthoclase. The biotite prisms are still oriented in the manner referred to above, but owing to the nature of their development unchanged pyroxene granules remain as inclusions. The relationship between these intergrowths and the biotite (and hornblende) is revealed by the bays and bights in the ends of the prisms and frequently by their presence in the more crystalloblastically powerful sides of the prisms.

The granulitic areas are composed of small rounded grains of pyroxene set in a matrix of plagioclase, probably labradorite, which has been formed by recrystallisation.

An imperfectly formed vein of quartz traversing the rock suggests that there has been a possible acquisition from without of silica which may have been effective in supplying this material to the amphiboles which are usually below the meta-silicate stage in rocks of this kind.

The existence of considerable hydrostatic pressure is evidenced by the presence of garnet crystals, and, this pressure, no doubt, has played a considerable part in the recrystallisation of the pyroxene.

A thin vein of chlorite, and some flakes of calcite suggest that in the very late history of the rock it has been subjected to a very slight metamorphism of a retrograde nature.

The rock is a little higher grade than No. 974. The hornblende-biotite masses are more coherent, and the granules of pyroxene are much more numerously developed. The greater abundance of pink garnet and the presence of some sphene indicate the greater degree of metamorphism the rock has undergone.

No. 973. Plagioclase Amphibolite.

This is another of the amphibolites which were found in the dykes which cross the gneiss on Stillwell Island. It is a little more schistose than is usual with this suite of rocks, but preserves the main characteristics, medium-grain size, black, dense, and hard.

The rock differs completely from those described by Stillwell from this source, but is much like certain plagioclase amphibolites from the moraines at Cape Denison which have come under notice, described by the present writer.

The ferromagnesians present are almost entirely confined to green compact hornblende whose pleochroism is strong and which has been described before in the place referred to above. The grains are nearly equi-dimensional, they are arranged in the decussate manner, usually they show the two amphibole cleavages quite well but where prismatic sections are seen only one cleavage is, of course, to be perceived.

Some brown biotite, passing into chlorite is present. There is also some green somewhat fibrous biotite, but here the alteration to chlorite is not quite so strongly developed. The only other dark mineral component is magnetite which occurs in fairly well-formed crystals, but irregular outlines are presented by some grains where neighbouring particles have coalesced to make a larger individual. Occasional skeletal crystals of this mineral occur.

The felspar which is the mineral second in abundance is andesine with Ab_{65} An_{35}. It is quite clear and usually gives sharp extinction. There is no doubt of its secondary nature. Its pellucid nature and the absence of every trace of original structure are conclusive evidence of this. It exhibits both albite and pericline multiple twinning, the latter sometimes appearing in very delicately defined lines which are unusually well-developed. A little quartz is associated with the plagioclase, but its amount is remarkably small.

Apatite occurs quite freely in small well-shaped rectangles, hexagonal basal sections, and prism sections. It is also found in the felspar as acicular rods which suggest that they have been able to resist the changed conditions which have so considerably affected the rest of the rock.

The presence of some few scales of calcite afford evidence that dynamic effects have been more potent in the alteration of the rock than heat, though, of course, the part played by the latter factor has been by no means inconsiderable.

No. 974. Hornblende-Plagioclase-Pyroxene Gneiss.

This rock, like No. 942, which was described by Stillwell, occurs in dyke-like bands up to 10 feet wide crossing the garnet gneiss. The rock is dark, dense, and fine-grained, although the granular nature is differential, in that there are fine-grained portions surrounded by more coarsely crystalline rock. One face of the hand specimen shows a remarkable development of pale brass-yellow sulphide ore, probably pyrrhotite. Of the faces which were exposed to weathering, one has the typically indurated appearance common to the rocks of this area, and another has been coloured yellow by the formation of some limonite by oxidation and hydration.

The rock may have been formed in the manner Stillwell suggests for No. 942, but the presence of an occasional crystal of pink garnet shows that the metamorphism suffered by the rock has been a little more intense, or that there has been a slight variation in the composition of the rock.

The rock, like No. 972, contains some hypersthene as well as monoclinic pyroxene, calcite, well formed grains of magnetite and some crystals of apatite. An occasional pleochroic halo, with zircon as-nucleus, is found in the biotite.

No. 977. Garnet-Plagioclase Amphibolite.

This is a moderately medium-grained, massive rock in which the most prominent minerals are red garnet and biotite. Hornblende is quite abundant and felspathic areas are readily observable.

The most striking feature of the rock is the presence of remarkable skeletal crystals of ilmenite whose peripheries are composed of many curved hooks or fingers which come from the main mass. Their relationships with the green hornblende of the rock is made manifest by the reaction zones which exist between the two. These reaction zones consist of a dactylitic intergrowth of felspar and pyroxene—called diablastic by Stillwell, but the term used here is preferable as it emphasises the finger-like nature of the components which enter into the intergrowth. The ilmenite is the nuclear region where concentration of iron (and titanium) from the hornblende is occurring: the dactylitic region shows where the actual diffusion of matter can be regarded as occurring. The source and the goal of the transfer are at once made evident.

Occasionally crystals of garnet are set in a rim of clear felspar which separates it from hornblende. In the felspar are to be seen very minute, but well shaped, rectangles of pale green amphibole which seem, in part, at least, to play a similar part to the pyroxene fingers in the transfer of material mentioned in the previous paragraph. These rims of felspar, with hornblende and sometimes biotite, are the reaction zones between the hornblende and the garnet nucleus. The possibility of felspar being potential hornblende to some degree at least is thus emphasised, and an indication is given that the relationship is reversible under suitable conditions.

Such masses of ilmenite, as previously referred to, are as frequently found associated with garnet as they are with hornblende. The fingers of the dactylitic intergrowth are still alternate bands of felspar and green pyroxene, but this time there is evidence that the pyroxene is a diffusion path of titanium as well as lime. It is quite usual to have the following serial relationships, hornblende connected to ilmenite nucleus by dactylitic felspar and pyroxene in a narrow rim, and then, the ilmenite nucleus connected to the garnet crystal by another such dactylitic rim, but this time, wider.

The garnet crystals have not assumed their perfect crystal outline, an indication that they are still undergoing the process of formation. They are remarkably embayed, and contain a large number of inclusions which include quartz, ilmenite, hornblende and biotite which produce the unusual effect of poikiloblastic garnets.

The other main minerals developed are hornblende, biotite, andesine and quartz. Accessory minerals include sphene, zircon in minute crystals, and apatite.

Rock No. 976 is merely a duplicate of this (No. 977).

No. 978. Garnet-Plagioclase-Amphibolite.

This rock, which was collected near the boat moorings, looks very much like No. 977, except that together with an increased micaceous content there has developed a more pronounced schistosity. This feature, however, has not been developed to such a degree as would warrant calling the rock a schist—it is still a gneiss. Another factor which favours a reduction in the gneissic nature of the rock is the smaller amount of garnet present, but, even so, garnet is still one of the most important minerals in the rock. Other minerals which can be recognised by the naked eye are hornblende and felspar.

Weathering has converted the biotite of the superficial layers into a golden coloured mica and has set free considerable quantities of oxidised iron compounds with the result that the exposed surfaces have assumed a deep yellow-brown colour.

The microscopic examination confirms the conclusions formed from the study of the hand specimen. Except for a slight increase in the amount of biotite present the rock differs in no material respect from No. 977. There is the same green, compact hornblende, garnet, ilmenite and hornblende in the same relations as before, and leucocratic areas of quartz and plagioclase.

III. ADDITIONAL PETROGRAPHIC NOTES ON ROCKS FROM MADIGAN NUNATAK.

1. INTRODUCTION.

A brief summary of Stillwell's description of the locality and the kinds of rocks found on the Nunatak is necessary.

He says (p. 128), " the Madigan Nunatak is situated in Lat. 67° 8½′ and Long. 143° 20′, about 30 miles distant from Cape Denison . . . , and 18½ miles from Cape Gray."

He gives photographic views of the Nunatak (Plate XXIV, figs. 1 and 2).

He further states, " it is composed of gneissic rocks whose foliation strikes approximately north and south " ; and " two rock types are found in this area. One is a black massive plagioclase-pyroxene-gneiss " which " seemed to form a band whose trend cuts at right angles across the foliation. The second type is the more abundant acid gneiss, containing blue quartz and hypersthene. In the neighbourhood of the anticline it has a banded character, but in other parts the gneissic character, though evident is less prominent."

2. THE PLAGIOCLASE-PYROXENE-GNEISS.

(a) *Modal Composition of Rocks.*

Stillwell has taken specimen No. 794 as the standard of this type of rock. Four other specimens were collected by Stillwell's sledging party in the summer, 1912–13. He has not given a description of any of these specimens, viz., Nos. 775, 783, 788, 792. They are readily seen to be akin to the standard but differences are none-the-less readily observed.

In the hand specimens the rocks are black, dense and fine-grained. They resemble very fine-grained dolerites when viewed macroscopically. The minerals seen in the hand specimens are pyroxene and felspar. As in the case of No. 794 the weathered surfaces of these specimens are discoloured by a brown iron stain.

The textures of the rocks shown by the microscope are granoblastic, " with subsequent modification by cataclastic effects." The average grain-size is about 0·25 mm., although No. 783 is somewhat finer, its average grain-size being approximately 0·17 mm.

The modal mineralogical contents of the rocks (determined by use of the Leitz Integration Table) are shown in the following table where they are compared with that of the reference specimen, No. 794 (determined by Dr. Stillwell).

Mineral.	No. 775.	No. 783.	No. 788.	No. 792.	No. 794.
Felspar	55·0	46·9	53·3	36·3	42·5
Pyroxene	32·4	32·4	38·1	36·6	45·5
Hornblende	1·1	...	2·2	21·8	3·3
Biotite	5·4	13·9	Present.	2·4	0·3
Iron Ore	6·1	6·8	6·4	2·9	8·4
Total	100·0	100·0	100·0	100·0	100·0

It will be seen that the general tenor of the rocks is the same, yet, notwithstanding this, notable variations occur. The felspar ranges from a minimum of 36·3 per cent. in No. 792 to a maximum of 55·0 per cent. in No. 775. The pyroxene of No. 775 is least, viz., 32·4 per cent. (the same amount as in No. 783) and that of No. 974 is most, viz., 45·5 per cent. A remarkable variation in the amount of hornblende is shown by the table. It is practically absent from No. 783 and yet in No. 792 it forms over one-fifth of the rock. A correlation between the inverse of felspar and hornblende can be drawn. Considerable variation is also shown in the biotite content, it reaches 13·9 per cent. in No. 783 and practically disappears in Nos. 788 and 794. The iron ore content is nearly uniform, although No. 792 differs somewhat from the rest.

A triangular graph (Fig. 16) showing percentages of felspar, F, pyroxene, P, and metamorphic matter, M (viz., hornblende + biotite + iron ores) is given. A serial relationship from C to E to A to B to D is seen. This shows the progression from minimum metamorphic matter in C to the maximum in D. (The letters A, B, C, D, E refer respectively to rock specimens Nos. 775, 783, 788, 792, 794.)

The diagram suggests that part of both the original felspar and pyroxene is taken up in the formation of these metamorphic products (hornblende, biotite, and iron ore), but this aspect of the matter will be treated more fully in part (*c*) below.

(b) *A Discussion of the Mineral Characters of the Rocks.*

As the Rosiwal analysis shows there are five main minerals present, felspar, pyroxene, amphibole, biotite, and iron ore. Accessory minerals include apatite and zircon.

The felspar present in all four rocks is plagioclase, although a little antiperthite is found in them all.

The natures of the various plagioclases present have been determined by refractive index methods and by the maximum extinction angles in the symmetrical zone.

Two of the rocks, viz., Nos. 783, 792, are like No. 794 of Stillwell in that they have two plagioclases present. In No. 783 there is a very small quantity of plagioclase which has $n_\alpha = 1 \cdot 538$ (approx.). Accordingly its chemical composition is oligoclase with $Ab_{80}\ An_{20}$. Most of the plagioclase in this rock gives a maximum symmetrical extinction ($X' \wedge 010$) of 20°, showing it to be andesine with $Ab_{63}\ An_{37}$. In No. 792 some of the plagioclase has n_α 1·535 and n_γ 1·545. This determines its composition as oligoclase with $Ab_{85}\ An_{15}$; but here again, most of the plagioclase is more basic. The extinction ($X' \wedge 010$) is 28°, corresponding to labradorite, $Ab_{48}\ An_{52}$.

The other two rocks, viz., Nos. 775, 788, carry only the more basic plagioclase, labradorite, whose composition is approximately $Ab_{50}\ An_{50}$.

The felspar in each of the four rocks shows both albite and pericline multiple twin lamellae. In every case the twinning is indistinct and tends to be discontinuous along the length of the laths. No. 792 has the least indefinite twin forms found in this suite of rocks, but even so there is a tendency towards the elimination of twinning in the central portions of the plagioclase grains. In No. 775 the concentric circular nature of the pericline twin lines is an indication of the deformations produced in this mineral by stresses.

Other stress effects are evidenced by the undulose extinction and the mortar structure associated with the peripheral granulation of the felspar.

None of the rocks shows saussuritised felspar, but every one contains felspar which holds inclusions of several kinds. No. 775 has abundant inclusions of magnetite dust, indiscriminately arranged flakes of biotite and green shreds of hornblende, and some crystals of zircon. No. 783 is much the same. The felspar of No. 788 is much cleaner, being practically free from hornblende and biotite inclusions, although it still has some magnetite and shows a new complication, viz., the presence of granulated pyroxene inclusions. There is a recurrence of the biotite flakes in No. 792, but here they tend to be arranged as tongue-like forms along cracks and cleavage lines rather than indiscriminate distributions through the grains as in No. 775. Magnetite dust is present in this specimen and also small granules of pyroxene (cf. No. 788), which are concentrated in the vicinity of larger grains.

These four rocks, like No. 794, contain both monoclinic and orthorhombic pyroxenes, the latter always being in considerable excess.

The orthorhombic pyroxene in No. 775 has $n_\beta = 1 \cdot 710$ (approx.), D.R. = 0·014. Its elongation is positive, its optic sign negative, 2V is large. These characteristics* are those of the hypersthene member of the enstatite-hypersthene series which carries a molecular percentage of 30 of $FeSiO_3$. In No. 783 n_α is slightly less than 1·680, which shows that the ratio $MgSiO_3 : FeSiO_3$ is greater, there only being 20 per cent. $FeSiO_3$ present. The mineral is still hypersthene.

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* Winchell, 1927, Vol. II, p. 177.

In all four rocks the hypersthene is pleochroic in light tones of green and pink; Z is always pale green and X light pink. The absorption is not strong, the formula is $Z \geq X$.

The monoclinic pyroxene in all four cases is a pale green to colourless augite. It is optically positive, 2V large, the extinction $(Z \wedge c)$ is about 45°, the D.R., 0·024.

In No. 792 occasional simple twins on 011 occur among the pyroxenes.

The pyroxenes are usually clear, but the augite of No. 792 exhibits good schiller structure, and not infrequently holds inclusions of magnetite (both as abundant dust and larger grains), flakes of biotite, felspar (and possibly a little quartz—the augite is here poikiloblastic), and hornblende.

Granulation, usually peripheral, of the pyroxene is evident in all four rocks, but more especially in No. 792.

Certain genetic relationships between the pyroxene and other minerals hold, but these will be discussed below.

The hornblende of No. 792 has as limits for its refractive indices $n_{\alpha} = 1{\cdot}66$, $n_{\beta} = 1{\cdot}67$, $n_{\gamma} = 1{\cdot}69$. The extinction $(Z \wedge c)$ is 15°. These data, according to Winchell (*op. cit.*, fig. 139, p. 224), correspond to that member of the pargasite-hornblende series whose chemical composition is approximately :—

	Per cent.
$NaFeSi_2O_6 + Fe_2O_3$	16
$CaMgSi_2O_6 + MgSiO_3$	42
$CaFeSi_2O_6 + FeSiO_3$	42

That is to say, it is a true hornblende. It is pleochroic, with Z brown-green, Y green-yellow, and X pale straw-yellow. The absorption is strong. The formula is the usual one, $Z > Y > X$.

In the other two rocks in which hornblende occurs to any appreciable amount (it is almost absent entirely from No. 783, see Rosiwal analysis above) it has the same characteristics as those given for No. 972. This rock was used as the standard of reference because of the greater abundance of hornblende in it.

The texture of the amphibole is usually granoblastic, although in places it is found in flakes and shreds. It holds frequent inclusions of magnetite (ilmenite). Its border is usually granulitic, in which respect it resembles the pyroxene.

The biotite of the rocks is deep reddish-brown in colour. It is pleochroic in lighter and darker shades, and has very strong absorption, $Z > Y > X$.

This biotite is associated with pyroxene, felspar, and ilmenite, frequently, but not always, with hornblende, and in No. 775 at least, with scaly calcite: it is intimately associated genetically with these associates, but see below, part (c).

It is always secondary (also see part (c)). In places, particularly in Nos. 783, 792, there are crystals whose curved outlines with sweeping bends suggest change of direction during growth produced by the variation of the prevailing stress-direction.

The magnetite (ilmenite) present in all these rocks has often been referred to above. Its mode of formation and other relationships to the remaining minerals will be treated below, see part (c).

(c) *Critical Analysis of Genetics of the Gneiss.*

We can assume that the original rock was a felspar-pyroxene one. If we suppose that the metamorphic products, M, represent both original felspar and augite, and that all the iron ores came from the augite (some, of course, may have been original), and the amphibole and mica came equally (the simplest assumption, though, necessarily, unsubstantiated) from the original minerals, the modal compositions of the parent rocks are as follows:—

Minerals.	No. 775.	No. 783.	No. 788.	No. 792.	No. 794.	Av. Comp.
Felspar	58·3	53·9	54·4	48·4	44·4	51·9
Pyroxene ...	41·7	46·1	45·6	51·6	55·6	48·1

We can justifiably assume that the original plagioclase was basic, a labradorite. It is not so easy to tell if the orthorhombic pyroxene is original, although Hatch (*op. cit.*, p. 415) suggests that hypersthene-gabbro, hypersthene-diorite and hypersthene-granite may possibly be formed by differentiation, which implies the original character of the hypersthene. If it is true as has been suggested (Tyrrell, 1930, p. 139) that one of the distinguishing features of the charnockite series—rocks from norite to pyroxene-granite—is the poverty of water-formed or water-rich minerals such as biotite and hornblende, then an accession of water must be postulated to account for the presence of these minerals in the present rocks.

3. The Hypersthene-Alkali-Felspar-Gneiss.

(a) *Macroscopic Features.*

Stillwell (p. 133, *et seq.*) has dealt with Specimens Nos. 795, 797 of this series. There remain Specimens Nos. 778, 779, 787, 790, 791, 793, 798, 1226, 1227, 1254 to be described.

These members of the second type of gneiss at the Madigan Nunatak are coarse-grained rocks in which the gneissic structure can be detected (cf., Stillwell, p. 133). This gneissic structure is much more prominent in some specimens than in others. For instance, very definite leucocratic and melanocratic bands are visible in Nos. 779, 787, but the texture of Nos. 798, 1226, 1227 is granulitic, and that of Nos. 778, 790, 791, 793, 1254, is best described as intermediate. The colours of the rocks taken as a whole also form a series from light to dark with an intermediate group where neither colour predominates. In the leucocratic group are Nos. 778, 790 and 1254, the intermediate group consists of Nos. 779, 791, 793, 798, 1226, 1227, and in the melanocratic group is No. 787. The macroscopically visible minerals are quartz (which is often blue, but sometimes brown), felspar and hypersthene. Weathering of these minerals has produced normally a brownish-red colouration, but more complete hydration has sometimes resulted in the production of a remarkable mustard-yellow coating which is particularly noticeable in No. 778. There is a considerable variation in the grain-size of these minerals. Not only is this noticeable in the case of the hypersthene (cf., Stillwell) but in the felspar and quartz as well.

(b) *Mineralogical Characters.*

These rocks consist of quartz, orthoclase and plagioclase as their most abundant constituents, but always with important hypersthene, biotite and ilmenite. Accessories are apatite, pyrites and zircon (or monazite).

Most of the felspar is orthoclase, which is highly perthitic. The small inclusions of plagioclase have a higher R.I. than their host. They are usually linearly arranged in a great number of parallel lines which preserve their parallelism extraordinarily well. The regularity of the size and spacing of the intergrowths is remarkable. No crystal of orthoclase has been observed which is not perthitic. These intergrowths, as a matter of fact, frequently follow a rectangular pattern, where, again, the regularity of size, arrangement and orientation is remarkable. In rocks where the orthoclase overwhelmingly preponderates (*e.g.*, No. 790) there is occasionally some multiply twinned acid plagioclase (albiclase, $Ab_{90}An_{10}$) which has perthitic inclusions in the sense used by Chudoba (Chudoba, translated by Kennedy, 1933, p. 18), that is, where the host has a lower refringence than its inclusions. In other rocks, *e.g.*, No. 1227, where more plagioclase is present, large areas of antiperthite are frequently found. Where the plagioclase is more abundant it shows multiple twinning badly defined, and has the other properties of a little more basic variety, viz., oligoclase, with $Ab_{80}An_{20}$ (approx.). These differences in the composition of the felspar units through a single individual give a distinctive appearance to the rock even when the nicols are parallel, but more so when they are crossed. This appearance is enhanced by the effects produced by the extreme cataclasis which the rock has suffered.

The quartz of the rock shows equally well the cataclastic effects. Often there has been produced in the rock a crude schistosity by the parallel elongation of the crushed portions (cf. Stillwell, p. 134). These effects are rendered more obvious under crossed nicols when the undulose extinction of the alternate bands differentiates one streak from the next.

Where quartz and felspar are contiguous the crushing has produced new effects. Myrmekitic intergrowths of the two minerals appear, usually in contact with a mosaic of equi-dimensional quartz particles on the side adjacent to this mineral and a well-developed mortar structure on the side abutting the felspar.

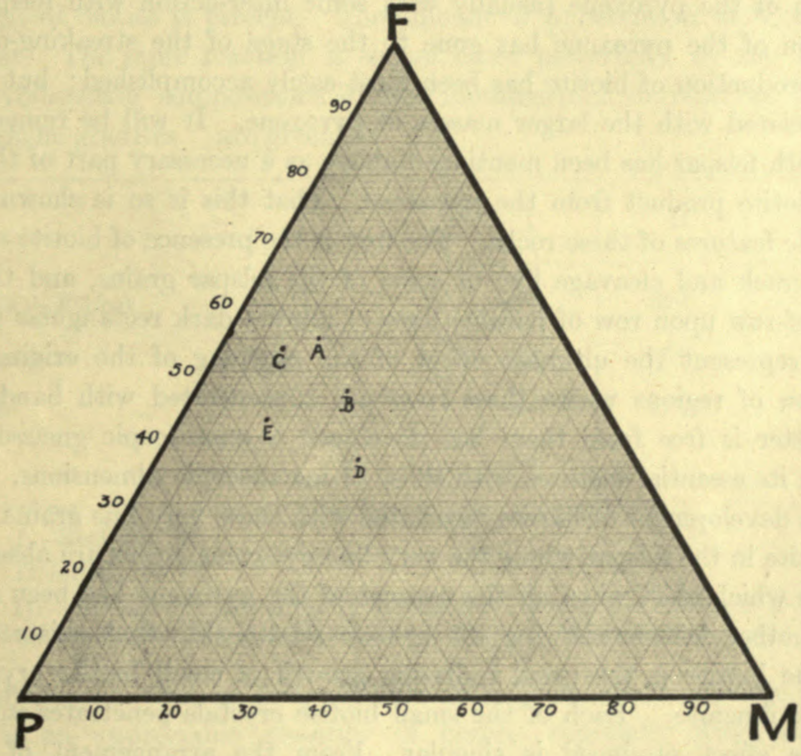

Fig. 16.

The pyroxene present is all hypersthene, which shows distinct pleochroism in pinks and greens, with Z green and X pink. The absorption is marked, the formula is $Z > X$. The appearance of the pyroxene is determined by the degree of cataclasis it has suffered and the extent to which it has undergone metamorphism. The second of these factors determines, to some extent, the amount of hypersthene present in the rock, but it is not the only influencing factor. The amount of original pyroxene is, of course, of importance. This is seen to vary from small quantities, as in Nos. 778, 790, 1227, 1254, to considerable amounts as in Nos. 779, 791, 1226. The degree of granulation appears to affect the readiness with which the pyroxene changes to ilmenite and biotite. The textural effects produced are the lenticular appearance of the larger grains (*e.g.*, No. 787), elongation of the grains (*e.g.*, No. 790), a parallel linearity of the grains (*e.g.*, No. 779) and streaked rows of minute granules (*e.g.*, No. 798).

The oblique extinction of some of the hypersthene suggested that the mineral might be monoclinic pyroxene. The low refractive index and the negative optic character of the mineral differentiated it from augite, and the parallel extinction of cleavage flakes established its orthorhombic nature. Merwin* observed the same phenomenon, and accounted for the oblique extinction by saying that the parting or cleavage developed was parallel to b (010). Doubtless the same explanation holds in this similar instance.

(c) *The Metamorphism of these Rocks.*

The biotite, ilmenite and hornblende of these rocks are the products of the metamorphism of the pyroxene (usually with some inter-action with felspar). Where the granulation of the pyroxene has gone to the stage of the streaking-out into fine granules the production of biotite has been most easily accomplished; but some of the biotite is associated with the larger masses of pyroxene. It will be remembered that inter-action with felspar has been mentioned above as a necessary part of the formation of the final biotite product from the pyroxene. That this is so is shown by at least two remarkable features of these rocks. The first is the presence of biotite streaks along nearly every crack and cleavage line of some of the felspar grains, and the second is the presence of row upon row of parallel lines of minute dark rectangular and rhombic grains which represent the ultimate effect of the crushing of the original pyroxene. The alternation of regions where these rows are concentrated with bands where the felspathic matter is free from them has developed a microscopic gneissose structure comparable in its essential features with those of macroscopic dimensions. Frequently there is seen a development of biotite associated with these very fine grains. The other streaks of biotite in the felspar where the very fine pyroxene grains are absent represent the conditions which exist when all the content of the pyroxene has been altered (*e.g.*, No. 793). Another feature showing the genetic relationship that exists between the felspar and the biotite is the usual radiating growth of small biotite crystals from a central core of ilmenite. Each of the small biotite crystals penetrates into felspathic material. The effect produced is singular. From the arrangement of these three minerals there can be no doubt that the growths represents a reaction between them.

4. SUMMARY.

From this treatment of the pyroxene-plagioclase-gneisses and the hypersthene-alkali-felspar-gneisses it will be seen that the acidity of the rock is the factor which determines whether the metamorphic derivative of the pyroxene shall be biotite or hornblende. In those rocks where the acid-felspar content is relatively low (*e.g.*, No. 792) the hornblende-content is great, but where the quartz-felspar-content is great (*e.g.*, No. 778, analysis below) hornblende is absent and the metamorphic derivative is biotite.

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* "The Charnockite Series of Igneous Rocks": H. S. Washington, Am. Jour. Sci., XLI (1916), p. 331.

The usual occurrence of pyroxene in rocks whose nature is definitely not acidic obscures this two-fold mode of its alteration. It is only in this so-called "Charnockite Series" that much pyroxene is found in definitely acidic rocks. It is, then, possible to find the metamorphic derivatives of pyroxene in acid surroundings in this suite only. Even so, the usual slight metamorphism which rocks of this suite from other regions have suffered has permitted Washington (*op. cit.*, p. 335), after citing the occurrence of the charnockite rocks from Norway, Ellesmere Land, New York and West Africa, to say that "biotite is rare or accessory and quite absent in most of the types." That this is not necessarily so in the metamorphic representatives of the suite is seen from the Rosiwal analyses of the "Intermediate Charnockites" Nos. 775, 783, where 5·4 per cent. and 13·9 per cent. of biotite is present. The amount of pyroxene in each of these rocks is 32·4 per cent. The same reaction is shown more powerfully by the following table where the volumetric compositions of two metamorphic derivatives (Nos. 778, 787) of "hypersthene granites" are given :—

	I	II	III
Quartz + Felspar	90·4	82·7	94
Hypersthene	6·7	6·0	3
Biotite	1·6	11·3	1
Ores	1·3	p.	2

I.—Rock No. 778.

II.—Rock No. 787.

III.—Specimen (9·658) of the Indian Survey. Occurs in central part of Magazine Hill, St. Thomas Mount, eight miles south of Madras. (Washington, *op. cit.*)

It will be seen that in each of these three rocks no hornblende has developed, but there is an appreciable quantity of biotite, especially when referred to the hypersthene—in No. 787 it is nearly twice as abundant.

It can be concluded then that amphibolization of the pyroxene is the characteristic alteration of this mineral in basic (and related) rocks, but that the formation of biotite is the characteristic metamorphic process in rocks which have original pyroxene and yet are acidic. Such rocks are the so-called hypersthene-granites and diorites and it must be among the comparatively rare metamorphic derivatives of these rocks that we must look to see the effects which have been suggested above. The rocks here described from Madigan Nunatak seem to be among the most interesting from this point of view.

DESCRIPTION OF PLATES.

PLATE XLIV.

Fig. 1. Cordierite-Garnet-Plagioclase-Biotite-Gneiss, Stillwell Island (No. 980).

The micro-photograph shows a mass of cordierite and biotite derived from the alteration of an earlier garnet crystal. Mag. 80 diams.

2. Hypersthene-Alkali-Felspar-Gneiss, Madigan Nunatak (No. 1227). The micro-photograph shows small biotite crystals proceeding from a large ilmenite grain and projecting into felspar. Mag. 44 diams.

3. Hypersthene-Alkali-Felspar-Gneiss, Madigan Nunatak (No. 778). The micro-photograph shows a synneutic aggregate of hypersthene in a matrix of felspar. Reaction between the hypersthene and the felspar has liberated ilmenite which has in places formed nuclei for biotite growths which project into the felspar. Mag. 35 diams.

4. The same rock as in Fig. 3.

A portion of the field of the previous photograph has been considerably enlarged to show more clearly the relation between the ilmenite, biotite and felspar. Mag. 170 diams.

PLATE XLV.

Fig. 1. Amphibolite occurring *in situ* near the Magnetograph Hut at Cape Denison (No. 421).

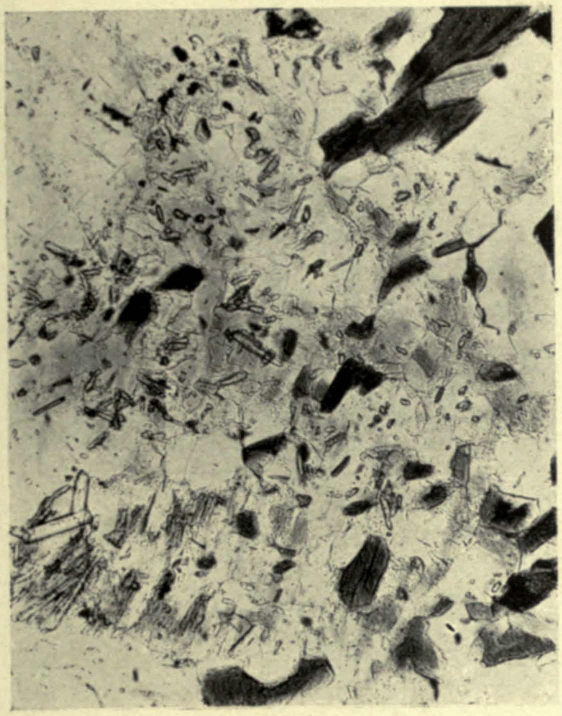
Crystals of sphene with nuclear ilmenite are shown together with biotite, felspar and a little hornblende. Mag. 35 diams.

2. Garnet-Plagioclase-Amphibolite, *in situ*, Cape Denison (No. 977). The micro-photograph shows a reaction zone where dactylitic growths of hornblende are the medium of transference of material from ilmenite to garnet via felspar. Massive hornblende is also seen in the field of view. Mag. 125 diams.

3. Hornblende-Plagioclase-Pyroxene-Gneiss, *in situ*, Cape Denison (No. 972).

The micro-photograph shows a circular region where earlier garnet has given place to a granulitic mass of pyroxene and felspar. Some remnants of the original garnet crystal remain. Mag. 44 diams.

Sydney: Thomas Henry Tennant, Government Printer—1940.



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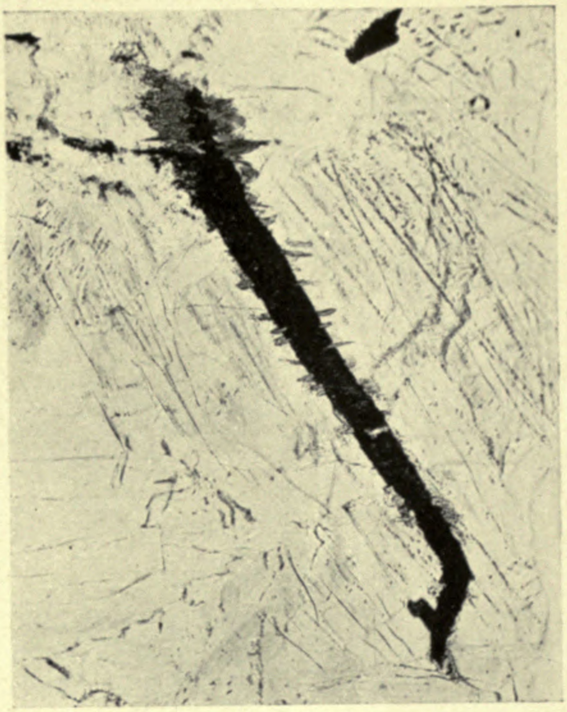


Fig. 2.

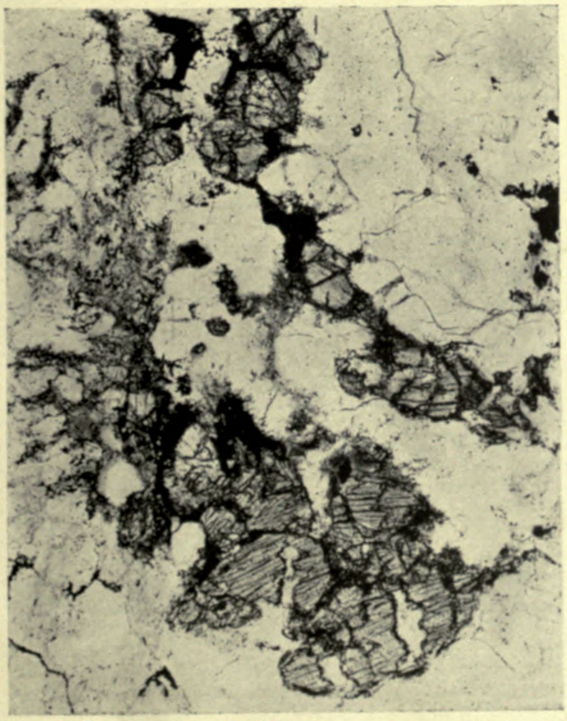
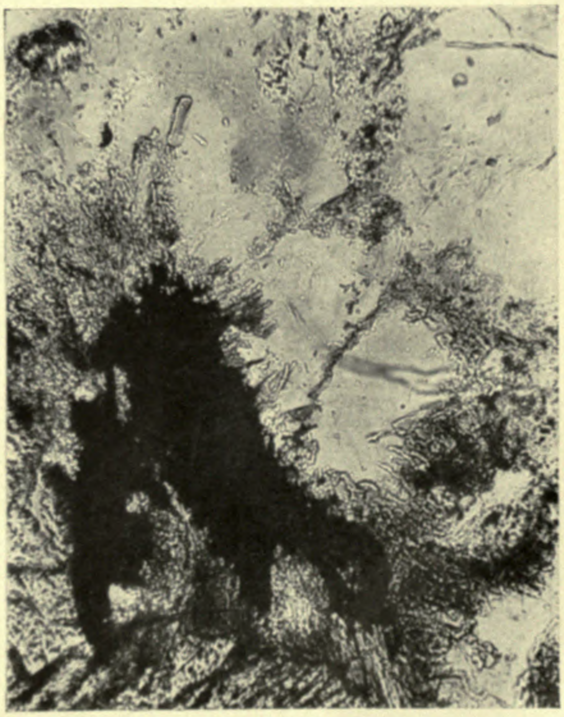


Fig. 3.



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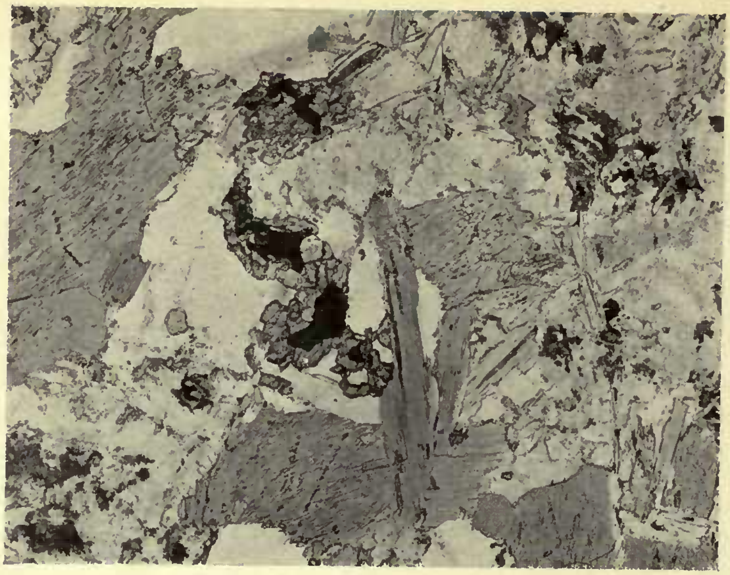

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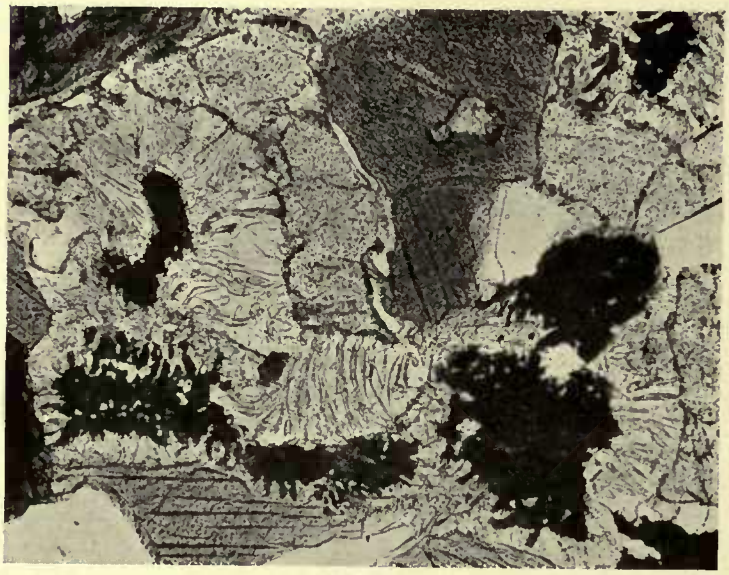

Fig. 2.

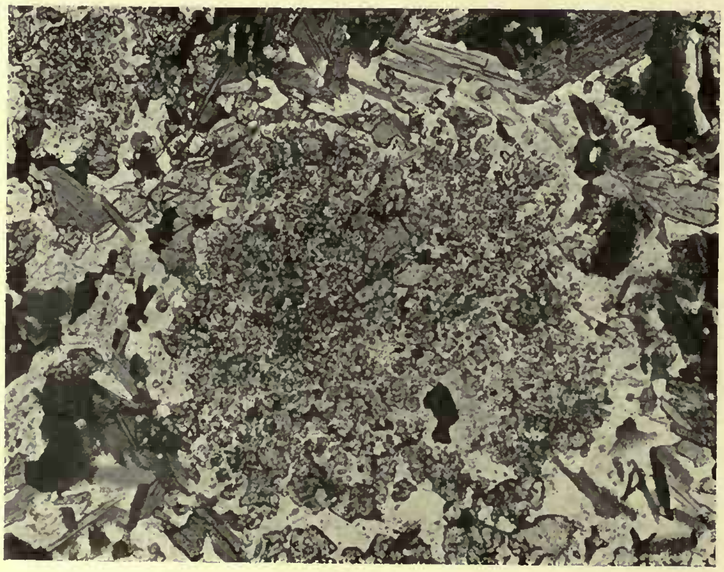

Fig. 3.

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